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September 1995

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Waterways Experiment Station

Flood Control Structures Research Program

Toe Scour and Bank Protection Using Launchable Stone

by Stephen T. Maynord, Douglas M. White

Prepared for Headquarters, U.S. Army Corps of Engineers

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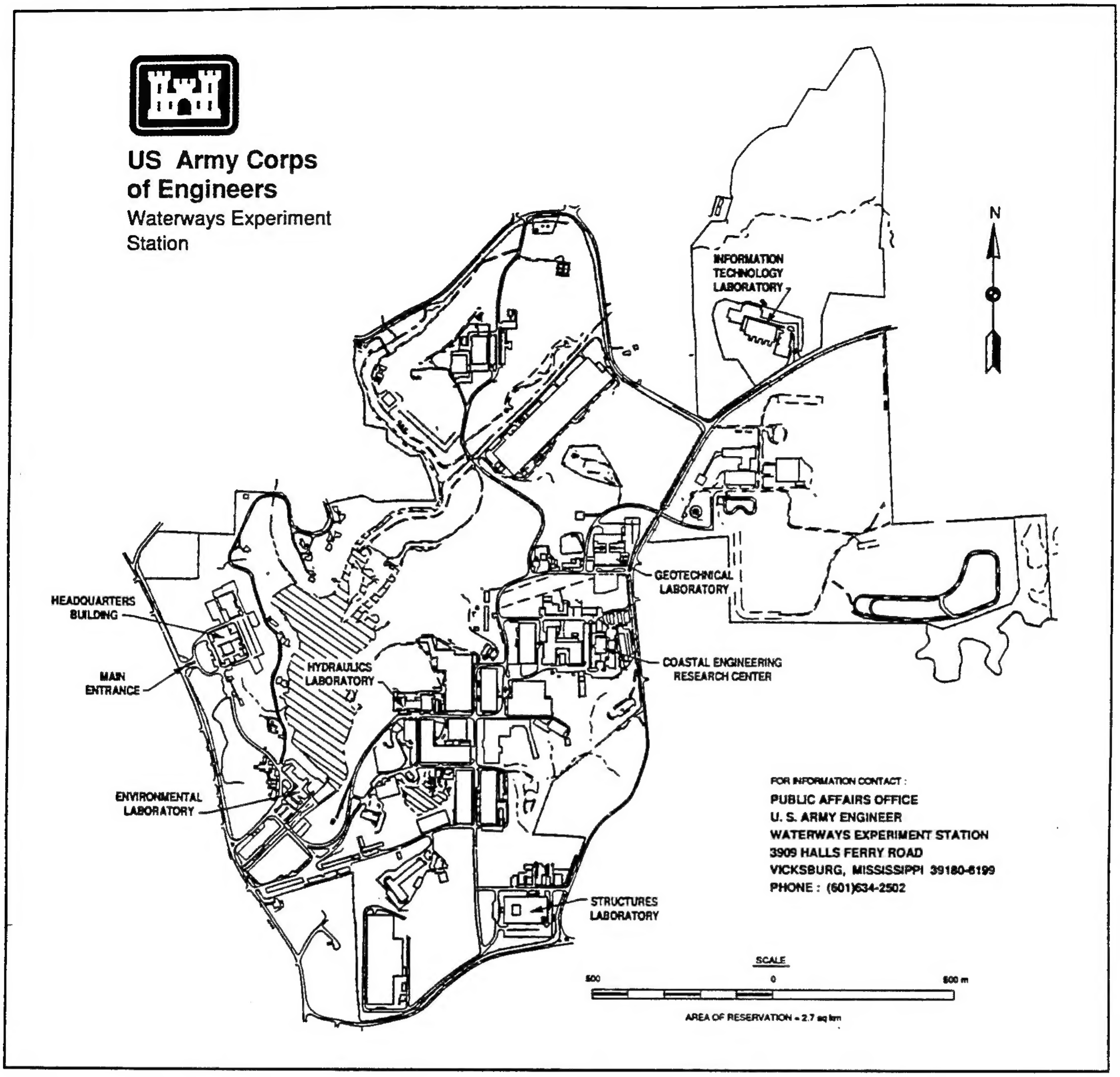

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Preface

The study described herein was performed by personnel of the Hydraulics Laboratory, U.S. Army Engineer Waterways Experiment Station (WES), during the period 1991-1993. This study was sponsored by Headquarters, U.S. Army Corps Engineers (HQUSACE), as part of the Flood Control Structures Research Program under Civil Works Investigation Work Unit 32686, "Riprap Toe and End Section Design." HQUSACE Program Monitor was Mr. Tom Munsey.

This study was conducted under the direction of Messrs. Frank A. Herrmann, Jr., Director of the Hydraulics Laboratory; Richard A. Sager, Assistant Director of the Hydraulics Laboratory; and Glenn A. Pickering, Chief of the Hydraulic Structures Division, Hydraulics Laboratory. The tests were conducted by Dr. Stephen T. Maynord, project engineer, and Mr. Douglas M. White, Spillways and Channels Branch, Hydraulic Structures Division, under the direct supervision of Mr. Noel R. Oswalt, Chief of the Spillways and Channels Branch. This report was written by Dr. Maynord and Mr. White. WES Program Manager was Dr. Bobby J. Brown, Chief, Hydraulic Analysis Branch, Hydraulic Structures Division.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Bruce K. Howard, EN.

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
degrees (angle)	0.01745329	radians
feet	0.3048	meters
inches	2.54	centimeters
pounds (mass) per cubic foot	16.01846	kilograms per cubic meter
square feet	0.09290304	square meters
square inches	6.4516	square centimeters

1 Introduction

Background

Bank erosion and scour in alluvial channels continue to trouble mankind because of the persistence in building structures in and near these channels, which conflicts with the natural tendency of the channel to move about. To prevent loss of structures adjacent to channels, various bank protection methods are employed, which vary in their effectiveness. Alluvial channels have numerous features that make long-term bank protection difficult. One of these difficulties is that the channel bottom, which often serves as the foundation for bank protection, tends to move up and down depending on several factors, one of which is a variable flow rate. Bendways, where most protection is placed, scour during high flows and fill during low flows. If bank protection is placed only down to the low-flow bed, high flow will often undermine and fail the protection. A second factor leading to a changing bed elevation is the change in cross section that occurs after bank protection is constructed. Unprotected cross sections tend to be relatively wide and shallow when banks are highly erodible. Once protection is placed on the outer bank of a bendway, the channel becomes narrower and deeper. Bank protection whose lower extremity is placed at the level of the unprotected channel bed will be undermined and possibly fail when the channel changes shape after being protected. Therefore, any bank protection method must be able to withstand movement or scour at the toe to provide long-term stability. Scour depth estimation is a critical part of toe protection design and is also described herein.

Two methods are used to prevent toe scour from undermining bank protection. The first method involves extending protection down to the maximum scour, which is often well below the existing or low-flow bed. This is often the preferred method in channels constructed in dry conditions. This method is expensive and difficult to accomplish in bank protection projects constructed in the "wet" (underwater). For construction in the wet, a second method of providing toe scour protection is to place an excess amount of riprap at the toe of the slope in what has been termed a "weighted toe." The loose riprap provides protection against undermining as the riprap migrates or launches downslope as erosion occurs beneath the riprap section. In addition to providing toe protection, launchable stone has been used to provide both bank and

toe scour protection in windrow revetments (placed at top bank) and trench fill revetments (placed at midbank to lower bank). A schematic showing a launchable stone section is shown in Figure 1.

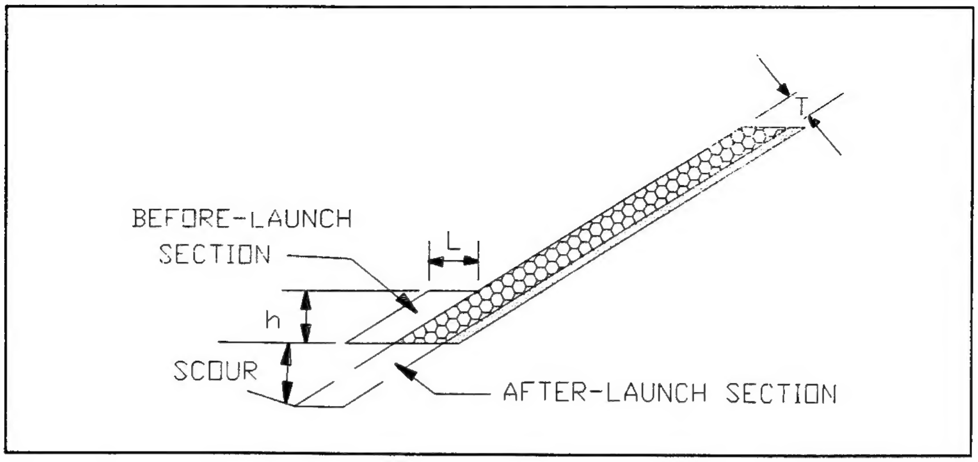

Figure 1. Launched stone schematic. As-built section can be placed above, on, or below the streambed

Objective and Scope

The objective of this study is to develop guidance for toe scour estimation and for design of launchable stone. Specifically the following questions are to be answered:

a. What are the impacts of toe shape? Is the aspect ratio L/h (length to thickness) or the thickness h the important parameter?

b. What is the impact of rock size? Does stream-launched riprap have to be larger than mechanically placed riprap?

c. What are the implications of using launchable stone in impinged flow environments where scour can be rapid?

d. What gradations are recommended for launchable stone?

e. What amount of stone is required to protect for a given scour depth?

f. What are the impacts of height of the launchable section above the maximum scoured elevation?

g. What increases in stone toe volume are required for underwater placement?

While the focus of this study will be launchable stone for toe protection, results will be generally applicable to windrow and trench fill revetments.

Other methods, such as concrete block and gabion mattresses, have been used for scour protection but are not addressed herein.

2 Scour Depth Estimation

Scour depth estimation is one of the more difficult aspects of the toe protection design process. "Rules of thumb" and past experience on the same or similar streams are widely used methods for scour depth estimation. Three-dimensional numerical models can be used to evaluate scour depth, but the effort required is generally beyond the resources available on most bank-protection projects. The empirical method in Engineer Manual (EM) 1110-2-1601 (Headquarters, U.S. Army Corps of Engineers (HQUSACE) 1994) is shown in Figure 2 and is based on data from Thorne and Abt (1993) and Mississippi River data shown in Table 1. The Mississippi River data were

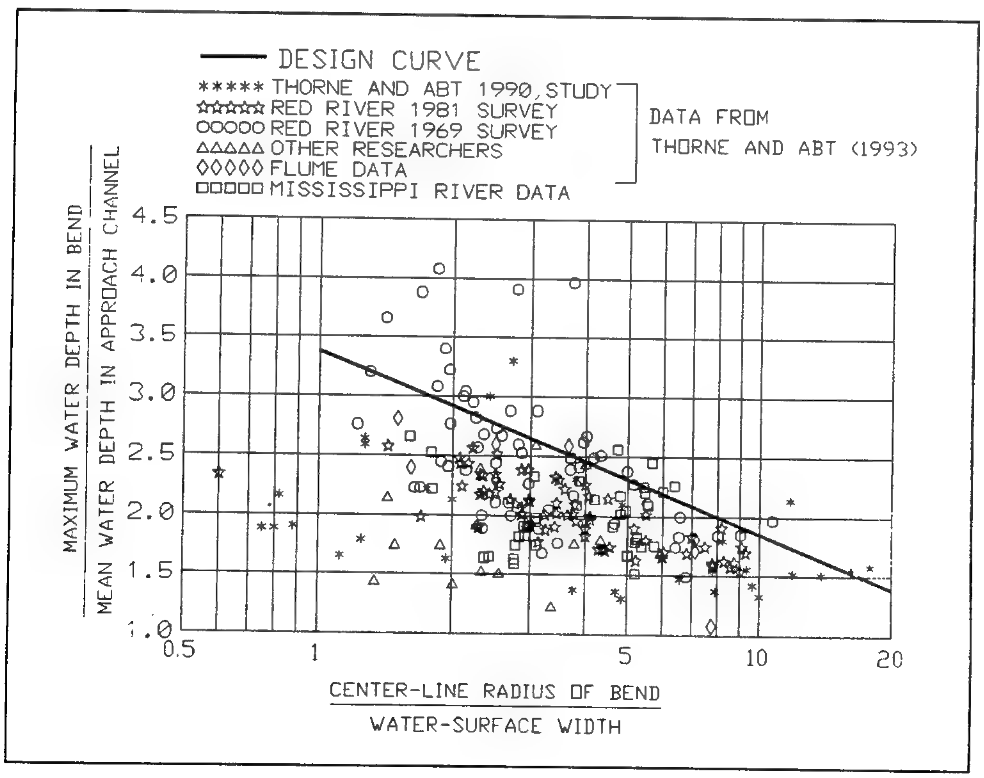

Figure 2. Scour depth guidance from EM 1110-2-1601

limited to discharges greater than 750,000 cfs[1]. Further analysis of these data shows that in addition to the ratio of center-line radius R to top width W, aspect ratio (width/average depth) is also a significant parameter. Certainly other parameters are significant, but their effects could not be determined from the data. The data were divided into the aspect ratio (AR) ranges shown in the following tabulation:

AR Name	AR Range	Number of Points	Average AR	Best Fit Line A, B[1]	R^2
25	9-40	58	23.7	0.252,2.17	0.20
60	40-100	137	62	0.338,2.52	0.28
125	100-210	29	127	0.633,3.42	0.18
2000	1,200-3,300	12	2,140	0.759,5.09	0.02

[1] $D_{max}/D_{bar} = -A \text{ in } R/W + B$

where

D_{max} = maximum water depth along the outer bank of the channel bend
D_{bar} = average water depth (area/top width) in the channel upstream of the bend, and
A and B = coefficients

The data for each range, plotted in Figures 3-6, clearly show increasing scour depth for increasing AR even though the correlation between dimensionless scour depth and *R/W* is poor. Because of the poor correlation, the best fit line cannot be used as a safe design curve to represent that range of AR. A safe design curve of 15 percent greater than the best fit curve is adopted in this study, as shown in Figures 3-6. The safe design curves are greater than about 80 percent of all data in each range of AR. Many of the data points falling above the safe design curves are for AR's greater than the average AR for that range. Using the safe design curves, only 10 points out of 222 (5 percent) had computed scour/observed scour less than 0.95, showing that the safe design curves are unconservative for only a small percentage of the data. The design curves with all data are shown in Figure 7. The scarcity of data for higher AR's suggests an upper limit of application of AR = 125. The advantage of Figure 7 over Figure 2 is that Figure 2 results in overestimation of scour depth in channels having low AR.

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[1] A table of factors for converting non-SI units of measurement to SI units is presented on page vi.

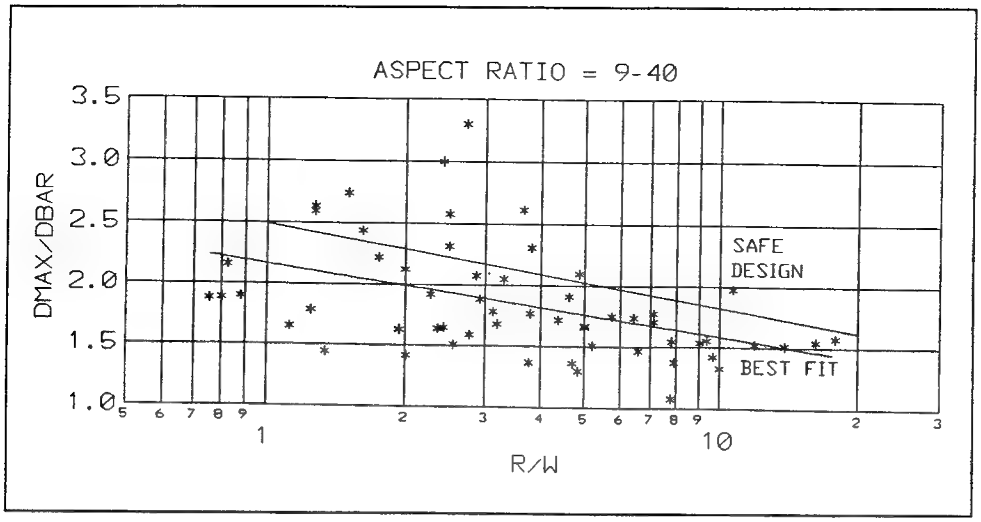


Figure 3. Dimensionless scour depth versus *R/W* for AR 9-40

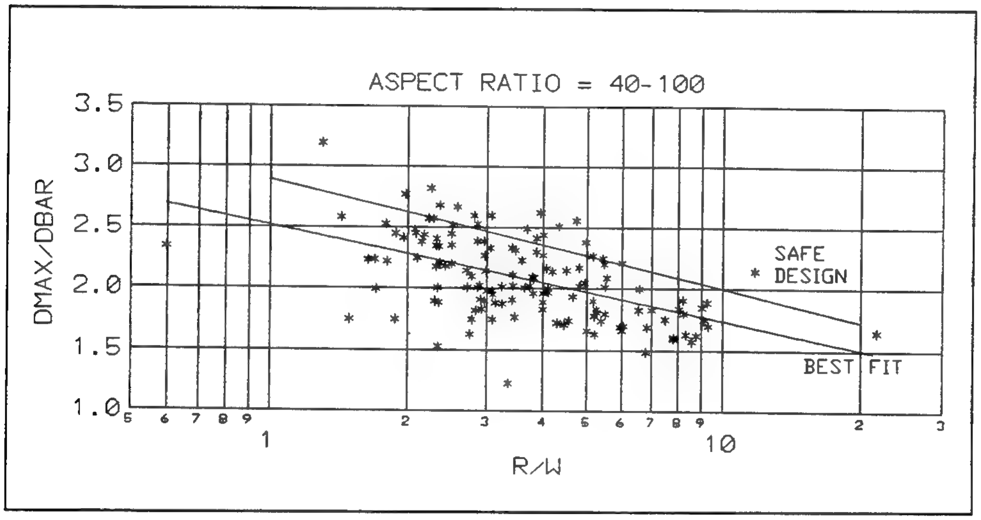


Figure 4. Dimensionless scour depth versus *R/W* for AR 40-100

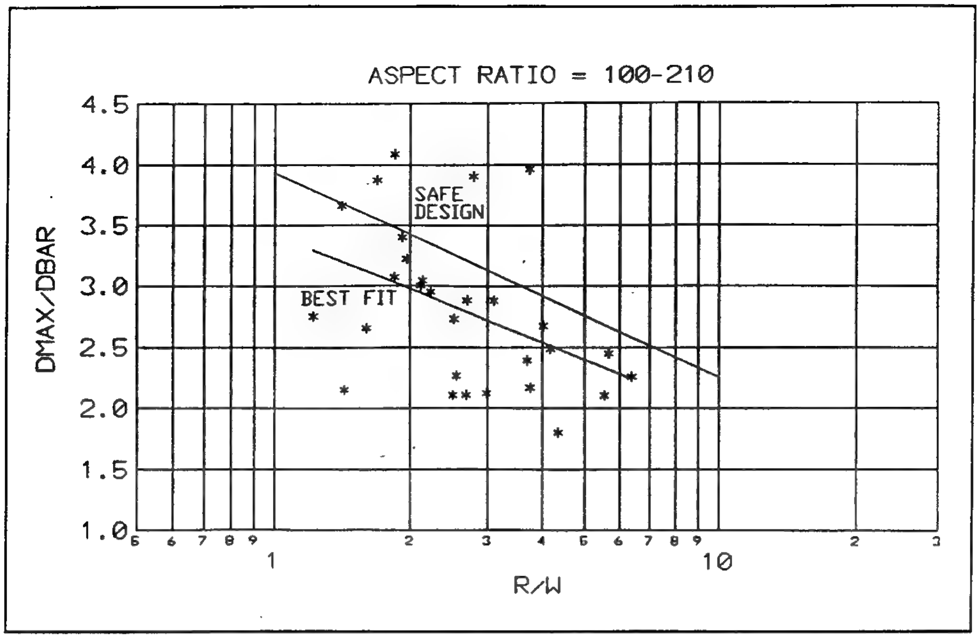


Figure 5. Dimensionless scour depth versus *R/W* for AR 100-210

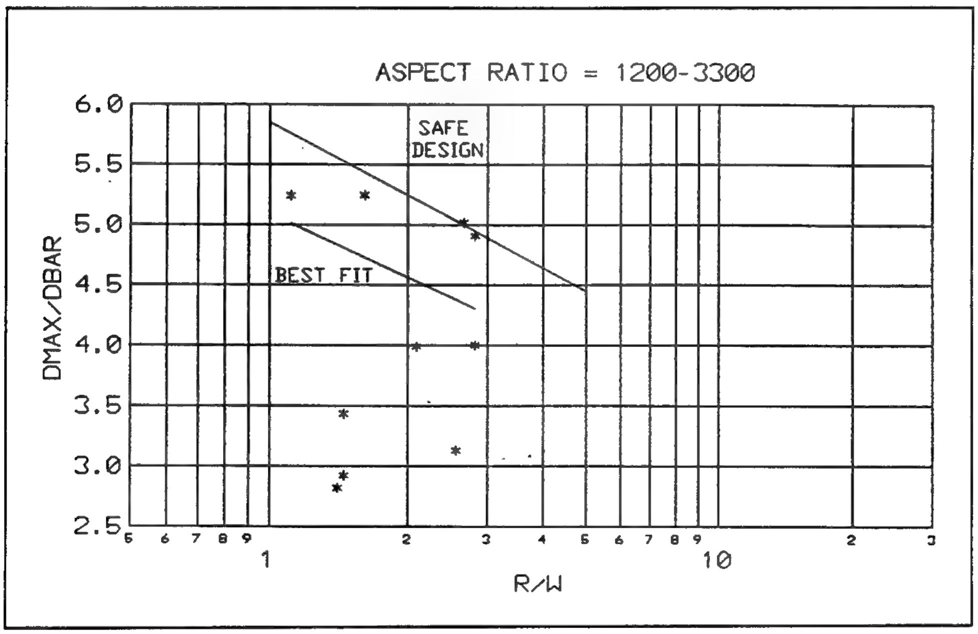


Figure 6. Dimensionless scour depth versus *R/W* for AR 1200-3300

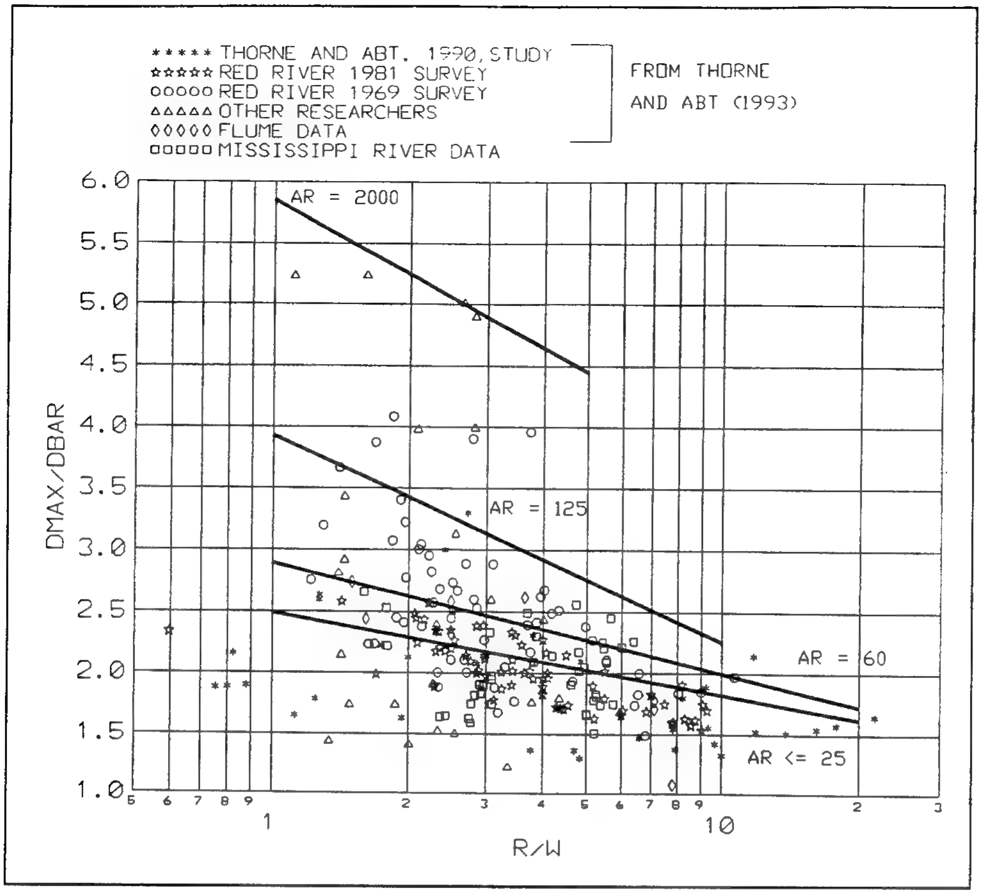


Figure 7. Dimensionless scour depth versus *R/W* for all data and safe design curves. Limit application to AR less than on equal to 125

3 Previous Launched Stone Studies

The earliest reference to launched aprons was found in Central Board of Irrigation and Power (CBIP) (1956), which relates the experience of Indian engineers with launching aprons as far back as the early 1900's. CBIP reports the following:

a. Average launch slope is 1V:2H.

b. "Model experiments and previous experience has [*sic*] shown that where scour was gradual, the slope and quantity of stone were practically the same whether the apron was laid deep and narrow or shallow and wide; but where scour occurred rapidly, a shallow wide apron would launch more gradually and evenly than a deep and narrow one. Under normal conditions a width, 1.5 times the scour depth, appeared optimum."

c. A wedge-shape design having apron thickness equal to $1.5T$ (T is the bank protection thickness, shown in Figure 1) at the toe of slope and $2.25T$ at the outer-apron end was recommended to account for the greater uncertainty in the launching process at the outer end of the apron. These thicknesses are used in conjunction with an apron width of 1.5 times the scour depth D_s. The resulting volume per unit length of bank line is $1/2(1.5T + 2.25T)(1.5D_s) = 2.81TD_s$. This is equivalent to a 25 percent increase in stone volume over the amount required to extend the bank protection to the full scour depth at a 1V:2H side slope and uniform thickness T ($5^{0.5}TD_s = 2.24TD_s$).

d. Aprons laid on alternating layers of sand and clay launch unevenly and require heavy maintenance and therefore should be avoided if possible.

e. It was found desirable to put larger stone in the outer end of the apron.

f. Graded mixtures were found to be more resistant than stones of a single size due to leaching of material through the revetment.

Jones (1966) reports on experience with weighted toes in the Snake River near Jackson, WY. In this reach, the Snake River is braided gravel bed stream

with multiple channels that frequently intersect levees at sharp angles. This flow condition at the levee has been referred to as impinged flow. Jones reports, "Not one example was found where the toe stone dropped and halted erosion. In every case where erosion undermined the toe, the riprap was completely washed away. The eroded stone was deposited in the main channel bottom usually several hundred feet from the damaged area." Rapid scour would be expected in this environment. No information could be found regarding the size, shape, or thickness of weighted toes used in this application.

A joint laboratory and field investigation of riprap toe structures was undertaken by the U.S. Army Engineer District, Omaha, on the Republican River below Milford Dam. The laboratory study reported in University of Nebraska (1969) tested various toe shapes for incorporation into the Milford channel. Model results showed the following:

a. Complex toe designs that are difficult to construct are not needed.

b. Good coverage of the launch slope was found with toes having a thickness of $3T$. Sparse coverage of the launch slope was found with a thickness of $2T$.

c. Toes that were too thick resulted in wasted stone in the launch process.

d. One layer was the maximum thickness of coverage observed on the launched side slope.

Several experimental toes and one design from the laboratory study were placed in the Milford outlet channel during 1966-1969. Inspections were made in 1974 and 1981 and reported in U.S. Army Corps of Engineers (USACE) (1981). The best performance was found with a horizontal toe placed to a uniform thickness of $2.5T$. Based on the 1974 survey, the toe having a thickness of $2.5T$ had an average launch slope of 1V:1.7H. It was concluded that a volume of stone equal to 50 percent greater than the volume required to extend the slope protection to the expected depth of degradation provided an economic and efficient method of protecting the revetment against damage by undercutting and was sufficient to withstand parallel flow conditions.

Neill (1973) recommends a volume of stone sufficient to cover the scoured slope to a thickness of 1.25 times the size of the largest stones in the specified grading. Most authors relate volume to the bank protection thickness T. This may be an important distinction since rock generally launches to a thickness of only one stone diameter.

U.S. Army Engineer Division, Missouri River (1984) conducted laboratory studies on windrows for bank protection and found the following:

a. Graded stone could not be failed by leaching whereas revetments formed of a uniform gradation could fail by leaching. The two graded stones tested had D_{85}/D_{15} of 1.7 and 1.9.

b. A rectangular section was found to be better than a triangular or trapezoidal section. Study results showed that "a certain amount of lateral erosion has to occur in order to permit the stone to feed down and cover the final bank slope. If all the windrow is within the erosion zone, ... , all of the stone will be undermined and the revetment overtopped, with failure occurring because of insufficient supply." Stated otherwise, a launchable stone section cannot have a large thickness and a narrow width.

c. The steepest launch slope observed in the model was 1V:1.7H, which was in the model having a bed made of crushed walnut shells. The sand bed model had consistently flatter launch angles.

d. "The size of stone used in the windrow is not a significant design parameter as long as the stone size is large enough to resist being transported by the stream."

e. "Although model results indicated that revetments with less than one stone diameter layer would function, it is suggested that the minimum thickness of 1.5 diam be used for design." Based on an example used in the report, the diameter was the mean diameter of windrow stone. The resulting toe volume based on the example in the report was equal to $3.1TD_s$ or 38 percent greater than the stone volume required to extend the protection to the full scour depth at a 1V:2H side slope and thickness *T*. Based on the example, the recommended height of the before-launch windrow section is $3T$.

Chohan, Shakoor, and Ahmad (n.d.) studied various shapes of horizontal aprons having uniform thickness from the toe of the bank to the outer end of the apron. Apron width and thickness combined to provide the same volume in all toes tested. Results showed the following:

a. Aprons of a thickness of $2T$ launched at a slope of 1V:3H. Flatter launch slopes generally mean less dense slope coverage, which can lead to leaching type failures.

b. "The conclusion to be drawn is that the width of the apron should be made as large as practical but not extending beyond the toe of anticipated fully launched slope, and its depth should not be less than 4 ft in any case." A thickness of 4 ft corresponds to $3.8T$. Chohan, Shakoor, and Ahmad's apron having a thickness of $2.9T$ lost the least volume of rock in the launching process. Aprons having a thickness of $5.7T$ or larger are inefficient because a large percentage of rock is lost in the launching process. Narrow and thick toes having thickness of $7.6T$ and $9.5T$ were the only toes to fail.

c. Results showed a greater percentage of rock lost in the launching process for greater vertical launch distance.

d. Increased stone weight in the apron decreased the rock lost in the launch process. It should be noted that Chohan, Shakoor, and Ahmad's model setup simulated relatively rapid scour.

Skrebkov et al. (1991) used model studies of "self placement of stone" in a design similar to the windrow revetment placed at the top of the bank. Unlike other reports, Skrebkov et al. places a sand berm adjacent to the eroding bank during low flow. The launchable stone section is then built on top of this sand berm. This ensures one of the requirements for a launchable section, namely that the section launches in noncohesive material to ensure a uniform rate of launching. Skrebkov found the following:

a. When the sand berm erodes to a slope of 1V:2.5H, individual stones begin to move down the slope. The slope continues to steepen, and when the slope reaches 1V:2H, mass movement of the stones begins down the slope. The stones, moving downward, wobble and turn, but do not turn over. The final slope is 1V:2H.

b. The thickness of the revetment layer in all experiments was equal to the size of one particle over the entire slope.

c. Maximum density of stone on the launched slope was obtained with a six-layer thickness in the stone section before launching. In a two-layer thickness the slope is not protected.

d. The larger stones in the gradation were found in the upper part of the launched slope, and smaller stones were found in the lower part of the slope.

e. Required stone volume was 1 to 1.2 times the volume of rock placed using standard construction techniques.

f. Launch sections are also being used in the wave environment, but results are not available.

HQUSACE (1991) presents guidance for design of toe protection. Four different toe sections are presented depending on type of channel bottom and magnitude of scour. Rock is assumed to launch on a 1V:2H slope, and a 50 percent increase in stone volume is used above the amount required for mechanical standard placement in dry conditions. Required volume becomes

$$\frac{Volume}{Unit\ length\ of\ bank} = 1.5\sqrt{5}\,D_sT = 3.35D_sT \qquad (1)$$

4 Experimental Investigation

Model Description

Launchable stone tests were conducted in the Riprap Test Facility (RTF), shown in Figure 8 and Plate 1. The RTF had riprap gradation 1 (Plate 2) placed to a thickness of 1.25 × D_{100} on the channel bottom and side slopes, except in the test section from station 1+80 to 3+32. The channel bottom in the test section was clean sand (free of gravel greater than 0.25 in.) from station 1+80 to 3+32. The outer bank side slope in the test section was covered with gradation 6 (Plate 2) to a thickness of 1.0 in. (1.0 × D_{100}) from station 2+22 to 3+00 on Tests 3 and 4. All subsequent tests had gradation 6 on the outer bank from station 2+10 to 3+15. Gradation 6 was used on the outer bank and in all toe designs except those addressing rock stability. Gradation 6 was based on HQUSACE (1991) stone size guidance using the 40-cfs discharge used in these toe tests. The inner bank of the entire test section was covered with gradation 1. The riprap on the outer bank of the test section was painted from the toe of the slope to a height of approximately 1 ft up the channel side slope from station 2+10 to 3+15 on each test. This was done to help determine if all of the toe design riprap had launched down into the scour zone at the completion of each test.

The channel side slope in the test section was 1V:1.5H for Tests 3-8 and 1V:2H for Tests 20-30 as shown in Table 2. Tests 1 and 2 were preliminary tests conducted with the original rock in the facility while a standard test procedure was being developed. No data were collected during these tests, and the first test to evaluate toe performance was Test 3.

The riprap gradation used in each toe design and each midbank design for all tests is shown in Table 3 and Plates 2-4. The shape characteristics and the angle of repose of the rock used herein are given in Maynord (1992). All rock was angular in shape.

Toe designs for Tests 3-8 and Tests 20-27 were molded at the toe of the outer bank for each shape as shown in Plates 5-7. All toe designs for Tests 3-27 had a volume of 0.111 cu ft per foot of bank along the toe.

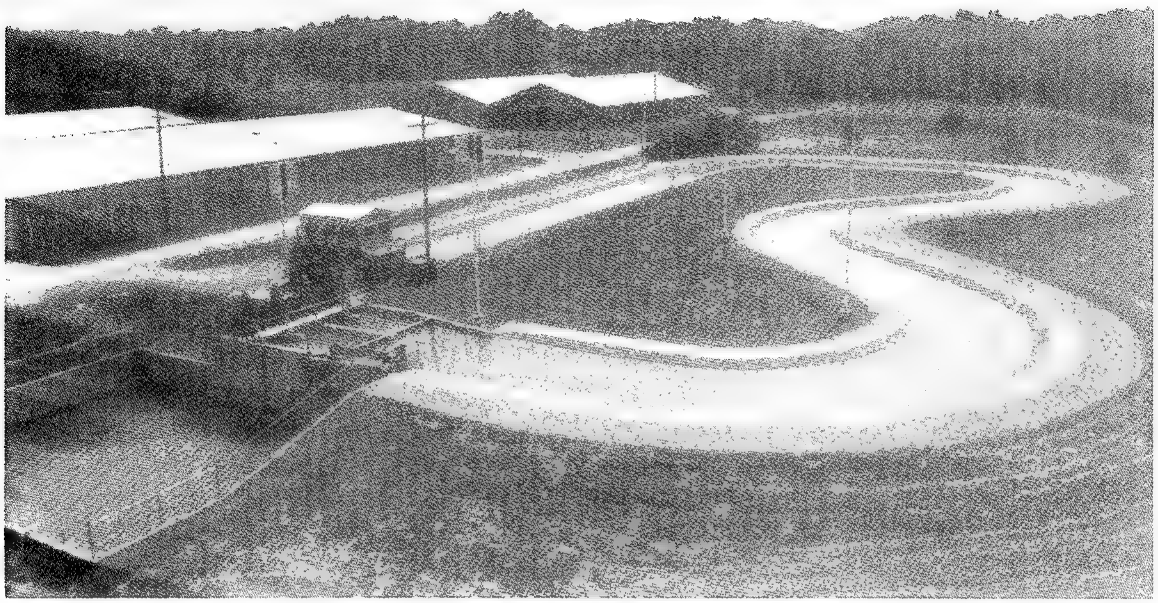


Figure 8. Riprap test facility

A berm with dimensions of 15 in. by 6 in. with a side slope of 1V:2H was molded with sand along the toe of the outer bank of the test section from station 2+10 to 3+15 to test toe designs placed near the middle of the bank similar to trench fill revetments. Midbank designs for Tests 28-30 were molded on top of the sand berm for each shape as shown in Plate 8. All midbank designs for Tests 28-30 had a volume of 0.165 cu ft/ft along the toe.

Test Procedure

To compare toe shapes, the toe section being tested was molded throughout the test section in the first bend. The model was run at a constant discharge of 40 cfs until a significant portion of the bend scoured deeply enough to deplete all rock in the launch toe section. Required test duration was generally 10-13 hr as shown in Table 2. Failing the toe section in the middle portion of the bend allowed determination of failure scour depths at both the upstream and downstream ends of the failed reach.

For each test, a pretest and posttest survey was taken across the channel at ranges every 5-10 ft from station 1+80 to 3+00 to show the cross section at each range. An example cross-sectional profile plot is shown in Plate 9. Elevations shown in Plate 9 are based on an arbitrary datum and are used only to determine differences between before and after test conditions. The

cross-section plots were not included in this report due to their large number. A toe scour elevation plot was plotted from the cross-sectional profiles on each test showing the maximum scour depth along the toe of launched slope. The results are shown in Plates 10-27. In Tests 3-25, run 1, except for Test 21, run 3, the slope of the launched stone was determined from the cross-section survey. In Test 21, run 3, and all tests after Test 25, run 1, the slope of the stone was measured for toe designs and midbank designs on each range by using a protractor and torpedo level, which was considered to be more accurate.

The failure criterion used in this study to compare different toe shapes was the point at which all toe design riprap was depleted, and painted channel side slope riprap was also being launched down into the scour zone. Upstream and downstream failure stations and depths are shown for each test in Table 2. Table 2 shows the basic launched stone data of each test for each toe design and each midbank design. Other toe design studies have used the percent of rock lost in the launching process to quantify toe performance. Measuring rock lost is difficult, and in a bend where scour depth is not constant, it is not possible to determine where the recovered rock came from. It was decided in this study that failure depth is a more significant parameter for comparing toe performance.

Scale Relations and Scale Effects

In this investigation, no absolute scale ratio was used to transfer results to prototype equivalents. Quantities were expressed in dimensionless terms so that results can be applied to a wide range of prototype conditions. In other tests, such as the toe shape tests, results for different shapes were compared to find if an optimum shape can be identified. These comparative tests did not involve transference of model quantities to the prototype.

To transfer quantitative dimensionless parameters, either the model must be free of scale effects or results must be adjusted for scale effects. The rock stability tests in this investigation were conducted in a sufficiently large model to be free of significant scale effects as discussed in Maynord (1992). The main concern with scale effects was the movement of sand through the launching stone as it begins to form a revetment on the launched slope. The sand, being the same size in the model and prototype, will be relatively easier to move in the prototype. The study areas that could be affected are the launch slope angle, the depth of scour an apron can withstand, and the evaluation of various gradations regarding leaching failures. Results from U.S. Army Engineer Division, Missouri River (1984) compared crushed walnut shells, which are easy to move, and sand in a physical model of launching stone. The walnut shells consistently launched on a steeper angle than the sand, which was attributed to the ease of movement of the walnut shells. Results from Milford Dam prototype in USACE (1981) show a 1V:1.7H launch slope for a toe having an h equal to $2.5T$. Results from University of Nebraska (1969) show a sand model launch slope of 1V:2H for an equivalent toe.

There is no rigorous method to adjust model results for these particle size scale effects. Design recommendations at the end of this report will consider the presence of scale effects in the model-derived parameters.

5 Analysis of Data and Results

Qualitative toe launching tests were conducted in a flume having a glass side to permit the observation of the movement of stone as the launching process occurred. Under conditions of gradual scour, the rocks crept down the launched slope. Very few rocks were observed to roll down the slope. Initial density of rock was low; but as erosion progressed, the rock density increased. The final slope was close to 1V:2H.

Downstream rock movement was studied for toe designs 7, 8, and 25. Toe designs 7 (gradation 14) and 8 (gradation 13) (Plate 5) consisted of rock having D_{30} of 0.036 and 0.031 ft, respectively. Toe design 25 (Plate 7) consisted of rock having D_{30} of 0.046 ft, which was the gradation 6 used in most of these tests. One test section 1 ft long by width of toe design 7 was molded in place at station 2+50 with a 6-in. length of the toe painted orange and a 6-in. length painted black. Both the orange and black rock moved downstream up to 14 in. Three test sections 6 in. long by width of toe design 8 were molded in place and painted orange at stations 2+45, 2+50, and 2+56 for Test 8. Downstream movement at all three sections was as follows: most less than 2 ft; some 4 to 5 ft.

Two test sections 2 ft long by width of toe design 25 were molded in place at stations 2+42 and 2+51 for Test 25. At station 2+42 the black riprap was placed on the lower half of the before-launch section, and the orange riprap was placed on the upper half of the before-launch section. After launching at station 2+42, the orange and black ripraps were fully mixed over the launched slope. At station 2+51 the orange riprap was placed on the inside half of the before-launch section, and the black riprap was placed on the outside half. Rock movement down the launched slope at station 2+51 showed orange riprap staying on the top half of the launched slope and the black riprap staying on the bottom half of the launched slope. No downstream movement of this larger gradation was observed, nor was the larger rock in the gradation located in any particular part of the toe.

Thickness of the after-launch riprap was studied after Test 24, run 2, was completed for toe design 24. Toe design riprap was removed at stations 2+35, 2+39, and 2+45. After these areas were reviewed, the conclusion was reached

that the launched riprap was approximately the thickness of the maximum stone size in gradation 6.

Lost riprap is the riprap at the bottom of the launched slope that is mostly parallel with the channel bottom and covered by sand. Lost riprap was recovered and measured on Test 5, run 2, through Test 6, run 2, for toe designs 5 and 6, and Test 30, run 2, for midbank design 30. The results of these tests are shown in Table 4. Approximately 14 percent of the original toe volume was found in the channel bed immediately adjacent to the toe of the launched riprap.

In Test 27, run 2, the model was stopped at 4.5 hr, 9.0 hr, and 13.0 hr. At these times a survey was made and toe scour elevations were plotted to show the maximum scour along the toe of the launched slope. Results (Plate 24) show that most of the scour took place in the first 4.5 hr.

Near-Bank Velocities

After toe design Test 24, run 2, was completed, the model was restarted and near-bank velocity measurements were taken along the test section. A one-dimensional pitot tube was used to take the measurements. On each range the near-bank location was determined by locating maximum scour depth and moving up the slope a distance of 20 percent of the distance between the location of maximum scour depth and the outer bank's water edge. The results of near-bank velocities are shown in Plates 28-33. As stated previously, gradation 6 was used on the bank and in most toe design tests. Gradation 6 was based on estimated velocity and stone size guidance given in HQUSACE (1991). The measured near-bank velocities were used to check the stability of gradation 6. The maximum depth-averaged velocity at 20 percent upslope from the toe was 2.83 ft/sec at station 300, and the local depth was 1.3 ft. This results in a required D_{30} of 0.040 ft based on center-line radius = 50 ft, water-surface width = 17.2 ft, unit stone weight of 167 lb/cu ft, thickness = $1D_{100}$, side slope = 1V:2H, and safety factor = 1.1. Gradation 6 has D_{30} = 0.046 ft, which is stable and relatively close to the size required based on the actual velocity.

Toe Shape Tests

Toe shapes were compared in the RTF to determine if the performance of a given toe shape was superior to those of other shapes. Only simple toe shapes were considered because many toe sections are constructed underwater, which precludes complex shapes.

During the toe shape tests, dunes were observed to move through the test section. When a posttest survey was conducted, the dune crests would occupy areas that were periodically the dune troughs during the tests. One item of

needed data was the scour depth at the observed downstream failure station. Often the failure station coincided with an area containing a dune at the end of the test. To obtain the maximum scour at the downstream failure station, depth was interpolated between the measured elevation at the adjacent dune troughs. To confirm that this was a valid assumption, the dune was excavated down to the lower level of the launched apron in Test 24, run 2. The elevation of the lower level of the toe was approximately equal to the interpolated elevation between troughs.

Table 5 summarizes the launched stone data for each toe design and each midbank design. The average launched slope was calculated as shown in Table 2 for each test, and an average value for each toe design is shown in Table 5. Detailed test results for each test are shown in Appendix A. Average failure depth and average launch slope were plotted against thickness of the before-launch section h as shown in Plate 34. Average failure depth is independent of h for the range of h tested herein and the gradual scour environment in the RTF. Launch slope decreases for the toes having values of h less than about 2.5-3T. This finding is similar to the results in U.S. Army Engineer Division, Missouri River (1984), which show that the application rate (i.e., h) controls the after-launch slope. This study shows this to be true for only low application rates (low h). Photographs of the launched slope for each value of h were examined to see if the flatter slopes also exhibit less dense slope coverage. Specifically the photographs were examined to see if more sand could be observed between the riprap particles. No significant difference in density of slope coverage could be observed.

The launched thickness value in Table 5 indicates the average rock thickness after launching for each toe design using its measured scour and measured launch slope. This ratio shows variation with the thickness of the before-launch section h. For weighted toes using gradation 6, after-launch thickness for $h > 2.5T$ is about 0.85 in. and for $h < 2.5T$ the after-launch thickness is about 0.66 in.

In the midbank tests with the sand berm, the launch slope angle shows a small but consistent decrease with decreasing h. Another small but consistent decrease in failure depth is observed with decreasing h. Comparing the berm tests with the weighted toe tests was not conclusive regarding the effects of vertical launch distance on toe performance.

In the gradual scour environment used in the bendway tested herein, toe shape based on before-launch thickness of 1.5 to 4.0 times the bank protection thickness T failed at about the same scour depth. This is consistent with findings in CBIP (1956). However, relatively flat launch slopes were found for values of h equal to 1.5 and 2.0T in the tests described herein, and sparse slope coverage was reported by University of Nebraska (1969) and Skrebkov et al. (1991) for $h = 2T$. The recommended h for gradual scour adopted herein is 2.5T to 4.0T. Based on Chohan, Shakoor, and Ahmad (n.d.), thickness greater than 4.0T launches rock at too fast a rate and wastes rock in the

launching process. All things being equal, the before-launch sections having $h = 3.0T$ are recommended.

Launched Stone Stability Tests

A series of launched stone stability tests were run after toe designs 6, 7, and 8 were completed. Tests 1S and 2S were run after toe design 6, Tests 3S and 4S after toe design 7, and Test 5S after toe design 8. A test section 20 ft long was located between stations 2+45 and 2+65 for Tests 1S-3S. In Test 4S, the test section was located from station 2+70 to 2+90. In Test 5S, the test section was located from station 2+40 to 2+75.

The toe design riprap was removed from the launched side slope in the test section, and nylon filter fabric was placed on the launched side slope. Riprap gradation 12 was used for Test 1S, gradation 13 for Test 2S, and gradation 14 for Tests 3S-5S. Riprap was placed on the nylon filter to a thickness equal to the maximum stone size in the gradation. Each test was run at 40 cfs for 10 hr.

Side slope velocities were taken during Tests 2S and 4S with a one-dimensional Pitot tube at station 2+55 on Test 2S and stations 2+55 and 2+80 on Test 4S. Velocity data were plotted and depth-averaged velocity was determined for both tests. The results are shown in Plates 35-37.

The failure criterion for the stability tests was exposure of an area of the nylon filter fabric greater than 2 in. in diameter. Failure occurred on Tests 1S-4S. Tests 3S and 4S may have failed because of undermining at the toe. Extra riprap was placed at the toe in Test 5S. Test 5S was borderline, having a 2-in. diam failure in the revetment. Detailed test results are shown in Appendix A. Results of these tests show that gradations 12 and 13 are unstable on the filter fabric and had significant downstream movement in the rock movement tests discussed previously. All tests have shown gradation 6 to be stable with no significant downstream movement during the launch process.

Launch and Placement Uncertainty

Concerning the amount of scour a given volume of stone can protect, the physical model results show that the rock launches to an average of $0.85T$ when using h greater than $2.5T$. Using a typical 1V:2H launch slope, the volume becomes

$$\frac{Volume}{Unit\ Length\ of\ Bank} = (0.85)\sqrt{5}\ D_s T = 1.9 D_s T \qquad (2)$$

U.S. Army Engineer Division, Missouri River (1984) also found that a thickness after launching of less than one stone diameter would function satisfactorily. For placement of toe sections in dry conditions, a minimum launch stone volume of 25 percent greater than the volume for standard placement on a 1V:2H slope is recommended to account for the uncertainty in launch process. Results from Chohan, Shakoor, and Ahmad (n.d.) show that the greater the vertical launch distance, the more stone lost in the launching process. Also to be considered is that toe structures are often placed underwater which is generally handled by increasing stone volume by 50 percent to account for the uncertainty in placement. An increase of 50 percent for uncertainty in underwater placement on top of the 25 percent increase for uncertainty in launching is overly conservative for many cases. The following increases are proposed to account for uncertainties in launch height and underwater placement:

Vertical Launch Distance, ft	Percent Increase in Stone Volume	
	Dry Placement	Underwater Placement
≤ 15	25	50
>15	50	75

Stone volume becomes

$$\frac{Volume}{Unit\ Length} = \left(1 + \frac{\%\ Increase}{100}\right) \sqrt{5}\ D_s\ T \tag{3}$$

Recommended Design Procedure

The recommended procedure for designing toe protection is as follows:

a. Compute scour using numerical models, past experience on the same or similar streams, or the empirical method shown in Figure 7.

b. Compute rock gradation and blanket thickness T using procedures in EM 1110-2-1601 (HQUSACE 1994). Specify a thickness of $1D_{100}$, 1V:2H side slope for launchable stone, and use stone having $D_{85}/D_{15} \geq 2$.

c. Compute volume/unit length of bank using Equation 3.

d. Determine appropriate before-launch thickness h = 2.5-4.0T for gradual scour and 2.5-3.0T for rapid scour.

e. Determine toe length L using h and required volume.

Example

The windrow example in U.S. Army Engineer Division, Missouri River (1984) had 30 ft of scour depth and a revetment thickness of 1.5 ft. The recommended design in U.S. Army Engineer Division, Missouri River (1984) resulted in a stone volume of 139 cu ft/ft of bank. The windrow section was 30 ft wide by 4.6 ft high (3.1T). Using guidance presented herein (Equation 3) for 30 ft of scour and dry placement results in $1.5(5)^{0.5}(1.5)(30) =$ 151 cu ft/ft. Assuming gradual scour, the windrow height can vary from 2.5 to $4.0T$ or 3.75 to 6.0 ft, respectively. The corresponding widths are 40 ft and 25 ft for windrow heights of $2.5T$ and $4.0T$, respectively. Using a recommended height of $3.0T$ results in $h = 4.5$ ft and an apron width of 33.6 ft, which is close to the Missouri River design.

6 Discussion of Results and Conclusion

An improved empirical method for scour depth estimation using dimensionless scour depth as a function of radius/width and aspect ratio is shown in Figure 7.

Concerning the impacts of toe shape, the thickness of the before-launch section *h* (Figure 1) controls the rate at which rock is launched and is adopted herein as the parameter defining toe shape. Proper launch performance occurs only in relatively noncohesive bed and bank materials. In a gradual scour environment, a before-launch section *h* of 2.5-4.0*T* is recommended for launching riprap sections. A value of $h = 3.0$ appears to be the best compromise between too thick sections that waste rock and too thin sections that result in sparse slope coverage.

In a rapidly scouring environment such as that found in impinged flow, the only toe shape information was found in CBIP (1956), that the shallow and wide toes work best. Based on this limited information, a toe shape based on $h = 2.5T$ to $3.0T$ is recommended for toes in a rapid scour environment.

Concerning the impacts of stone size, results from the studies conducted in the RTF representing gradual scour show that the stone size used in riprap revetments placed by standard placement methods is stable for launching riprap. For rapid scour, results are not as clear. Jones (1966) reports poor performance of the launchable stone in an impinged flow environment where rapid scour would be expected. However, no information is presented that would lead to conclusions about the cause of failure. Rapid scour will result in stones moving down the launch slope faster than the creeping motion observed in the glass-sided flume, as described in Chapter 5, "Analysis of Data and Results." This faster downslope movement could lead to a decrease in stability. A 10-20 percent stone size increase above the size required for standard placement techniques is recommended for launchable stone in rapid scour environments.

Regarding recommended gradations, U.S. Army Engineer Division, Missouri River (1984) found stones having D_{85}/D_{15} of 1.7 and 1.9 could not be failed by leaching. Tests conducted herein with D_{85}/D_{15} of 2.0 or greater

did not fail by leaching. Gradations having $D_{85}/D_{15} > 2.0$ are recommended because this is one area that can be affected by the previously discussed scale effects. A minimum $D_{85}/D_{15} = 2.0$ is recommended.

Concerning the amount of scour a given volume of stone can protect, Equation 3 and the tabulation for percent increase in stone volume presented in Chapter 5, are recommended for design.

References

Central Board of Irrigation and Power. (1956). "River behavior, control and training," Publication No. 60, New Delhi, 143-146.

Chohan, M. A., Shakoor, A., and Ahmad, S. (n.d.). "Some experiments on shape of spurs," Report CIV-CON-87/5, Punjab Irrigation Research Institute, Lahore, Pakistan.

Headquarters, U.S. Army Corps of Engineers. (1991 (1 Jul)). "Hydraulic design of flood control channels," EM 1110-2-1601, U.S. Government Printing Office, Washington, DC.

Headquarters, U.S. Army Corps of Engineers. (1994 (30 Jun)). "Hydraulic design of flood control channels," EM 1110-2-1601, Change 1, U.S. Government Printing Office, Washington, DC.

Jones, A. B. (1966). "Snake River bank stabilization," *Journal Waterways and Harbors Division*, ASCE, 92(WW1), 1-16.

Maynord, S. T. (1992). "Riprap stability: studies in near-prototype size laboratory channel," Technical Report HL-92-5, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Neill, C. R., ed. (1973). "Guide to bridge hydraulics," Roads and Transportation Association of Canada, University of Toronto Press, Toronto, 133-136.

Skrebkov, G. P., Afim'ina, K. A., Mukin, V. A., and Korotkov, V. E. (1991). "Protection of underwater slopes by self-placement of stone," *Hydrotechnical Construction* 25(5), 273-275.

Thorne, C. R., and Abt, S. R. (1993). "Velocity and scour prediction in river bends," Contract Report HL-93-1, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

University of Nebraska. (1969). "Laboratory investigation of performance of riprap toe structures with channel degradation," Performed under Contract No. DACW45-68-C-0121 by the University of Nebraska, River Engineering

Laboratory, Mead, NE, for the U.S. Army Engineer District, Omaha, Omaha, NE.

U.S. Army Corps of Engineers. (1981). "Final report to Congress, The Streambank Erosion Control Evaluation and Demonstration Act of 1974, Section 32, Public Law 93-251," Washington, DC.

U.S. Army Engineer Division, Missouri River. (1984). "Laboratory tests to design windrow revetment for bank protection," Missouri River Division Hydraulic Laboratory Series Report No. 7, Mead Hydraulic Laboratory, Mead, NE.

Table 1
Mississippi River Scour Data

Bend Name	Date	Area, sq ft	Width, ft	Maximum Depth, ft	Radius, ft	Discharge, cfs
Catfish	3/67	137,138	2,507	95	13,500	794,030
	4/69	151,804	2,732	114	13,500	1,089,950
	3/72	141,341	2,350	105	13,500	829,670
	5/67	140,788	2,573	100	13,500	993,960
	3/68	158,106	2,600	108	13,500	997,650
	5/70	159,958	2,568	113	13,500	1,129,300
Cypress	3/67	127,935	2,703	90	8,000	825,180
	4/69	174,424	2,905	98	8,000	1,142,480
	3/72	127,022	2,600	97	8,000	795,160
	5/67	135,777	2,760	94	8,000	943,650
	3/68	153,355	2,823	99	8,000	993,740
	5/70	172,361	2,880	105	8,000	1,204,800
Prentiss	6/68	203,951	3,600	104	10,500	1,121,730
	2/69	163,864	3,400	94	10,500	929,110
	5/70	216,160	3,400	111	10,500	1,348,840
Arkansas Yellow	2/68	123,182	1,880	104	5,200	870,900
	4/69	148,166	2,140	114	5,200	1,087,540
	5/70	157,310	2,200	117	5,200	1,101,170
Fittler	4/69	198,261	4,000	110	7,200	1,001,220
	3/71	201,122	4,500	119	7,200	1,170,530
Cottonwood	4/69	156,156	2,500	104	12,500	968,170
	3/71	171,759	2,500	115	12,500	1,190,290
Belle Island	4/70	168,968	3,385	110	18,500	946,220
	5/68	167,335	3,332	105	18,500	808,230
Milliken	4/70	180,645	3,435	121	13,300	896,000
	5/68	167,601	3,602	116	13,300	814,540
Grand Gulf	3/71	176,764	3,405	117	18,500	1,138,360
Hardscrabble	3/71	205,371	2,750	143	12,700	1,139,810
	12/71	143,843	2,644	118	12,700	798,330

(Continued)

Table 1 (Concluded)						
Bend Name	**Date**	**Area, sq ft**	**Width, ft**	**Maximum Depth, ft**	**Radius, ft**	**Discharge, cfs**
Walnut Point	2/69	189,612	4,500	103	25,500	1,255,230
	3/71	157,466	4,000	89	25,500	851,890
Kentucky	2/68	128,852	2,600	100	12,500	782,130
	2/69	118,802	2,640	115	12,500	823,300
Mayersville	2/69	169,685	3,100	117	13,000	1,033,380
	2/71	171,758	2,500	104	13,000	843,330
Bougere	12/72	201,585	3,640	140	6,500	1,102,670
Lake Karnac	1/70	138,311	2,800	103	10,700	756,560
	3/71	191,244	3,500	127	10,700	1,168,500

Table 2 (Concluded)

Test No.	Toe Design	AR	Gradation No.	Thickness T	Side Slope	Test Duration hr	Upstream Failure Sta	Upstream Failure Depth ft	Downstream Failure Depth ft	Downstream Failure Depth ft	Maximum Scour Depth ft	Average Launched Slope
23R1	23	1.255	6	4	1V:2H	10	225	0.60	265	0.63	0.93	1V:2.0H
23R2	23	1.255	6	4	1V:2H	10	227	0.70	270	0.65	0.89	1V:1.85H
24R1	24	4	6	2	1V:2H	13	229	0.75	258	0.65	0.94	1V:2.3H
24R2	24	4	6	2	1V:2H	13	235	0.86	250	0.66	0.86	1V:2.65H
25R1	25	2.6	6	2.5	1V:2H	13	236	0.86	254	0.66	0.95	1V:2.45H
26R1	25	1.8	15	3	1V:2H	13	236	0.82	268	0.58	0.84	1V:2.1H
26R2	26	1.8	15	3	1V:2H	13	232	0.85	255	0.63	0.92	1V:2.0H
27R1	27	1.8	16	3	1V:2H	13	230	0.80	255	0.72	0.80	1V:2.0H
27R2	27	1.8	16	3	1V:2H	13	225	0.65	258	0.63	0.88	1V:2.0H
28R1[2]	28	6	6	2	1V:2H	10	225	1.18	270	0.97	1.30	1V:2.3H
28R2[2]	28	6	6	2	1V:2H	8	225	1.15	277	0.97	1.24	1V:2.3H
29R1[2]	29	2.7	6	3	1V:2H	10	230	1.24	250	1.05	1.43	1V:2.15H
29R2[2]	29	2.7	6	3	1V:2H	10	225	1.19	260	1.19	1.40	1V:2.1H
30R1[2]	30	1.5	6	4	1V:2H	10	224	1.34	288	1.34	1.40	1V:2.0H
30R2[2]	30	1.5	6	4	1V:2H	10	230	1.30	269	1.30	1.35	1V:2.1H

[2] Tests 28 through 30 maximum scour depth's base zero is +0.50 at top of sand berm.

Table 2
Basic Launched Stone Data

Test No.	Toe Design	AR[1]	Gradation No.	Thickness T	Side Slope	Test Duration hr	Upstream Failure Sta	Upstream Failure Depth ft	Downstream Failure Depth ft	Downstream Failure Depth ft	Maximum Scour Depth ft	Average Launched Slope
3R1	3	1.8	6	3	1V:1.5H	8	227	0.72	256	0.68	0.82	1V:2.05H
3R2	3	1.8	6	3	1V:1.5H	10	227	0.65	258	0.55	0.78	1V:2.2H
4R1	4	1	6	4	1V:1.5H	10	230	0.80	260	0.60	0.90	1V:2.1H
4R2	4	1	6	4	1V:1.5H	10	225	0.70	270	0.66	0.91	1V:2H
5R1	5	4	6	2	1V:1.5H	10	225	0.66	247	0.70	0.88	1V:2.8H
5R2	5	4	6	2	1V:1.5H	10	253	0.80	255	0.74	0.85	1V:2.6H
6R1	6	7.1	6	1.5	1V:1.5H	10	247	0.72	255	0.72	0.88	1V:3.25H
6R2	6	7.1	6	1.5	1V:1.5H	10	230	0.72	258	0.61	0.80	1V:2.95H
7R1	7	1.8	14	3	1V:1.5H	10	230	0.79	256	0.61	0.88	1V:2.45H
8R1	8	1.8	13	3	1V:1.5H	10	236	0.82	270	0.53	0.88	1V:2.45H
20R1	20	1.8	6	3	1V:2H	10	234	0.64	253	0.60	0.87	1V:2.05H
20R2	20	1.8	6	3	1V:2H	10	230	0.69	252	0.70	0.90	1V:2.6H
21R1	21	7.1	6	1.5	1V:2H	10	230	0.70	252	0.57	0.88	1V:2.7H
21R2	21	7.1	6	1.5	1V:2H	10	230	0.90	250	0.90	0.90	1V:2.4H
21R3	21	7.1	6	1.5	1V:2H	10	228	0.72	237	0.65	0.84	1V:2.35H
22R1	22	1	6	4	1V:2H	10	233	0.83	255	0.75	0.83	1V:2.1H
22R2	22	1	6	4	1V:2H	10	225	0.65	250	0.77	0.90	1V:2.1H

[1]Toe width/Toe depth.

(Continued)

Table 3
Riprap Characteristics

Gradation No.	D_{85}/D_{15}	γ_s pcf	D_{30} ft	Plate No.
1	1.9	171	0.097	2
6	2.1	167	0.046	2
12	2.1	167	0.023	2
13	2.0	167	0.031	3
14	2.1	167	0.036	3
15	2.8	167	0.033	4
16	3.0	167	0.042	4

γ_s = unit weight of stone.

Table 4
Basic Lost Riprap Data

Test No.	Section No.	Station Location	Amount Recovered cu ft	Percent of Total
5R2	1	2+31 - 2+34	0.046	14
5R2	2	2+40 - 2+43	0.046	14
5R2	3	2+50 - 2+53	0.043	13
6R1	1	2+31 - 2+34	0.042	13
6R1	2	2+40 - 2+43	0.041	12
6R1	3	2+50 - 2+53	0.060	18
6R2	1	2+30 - 2+33	0.040	12
6R2	2	2+38 - 2+41	0.034	10
6R2	3	2+52 - 2+55	0.053	16
30R2	1	2+30 - 2+33	0.072	14
30R2	2	2+35 - 2+38	0.071	14
30R2	3	2+40 - 2+43	0.117	23
30R2	4	2+50 - 2+53	0.070	14
30R2	5	2+65 - 2+68	0.079	16

Table 5
Summary of Launched Stone Data

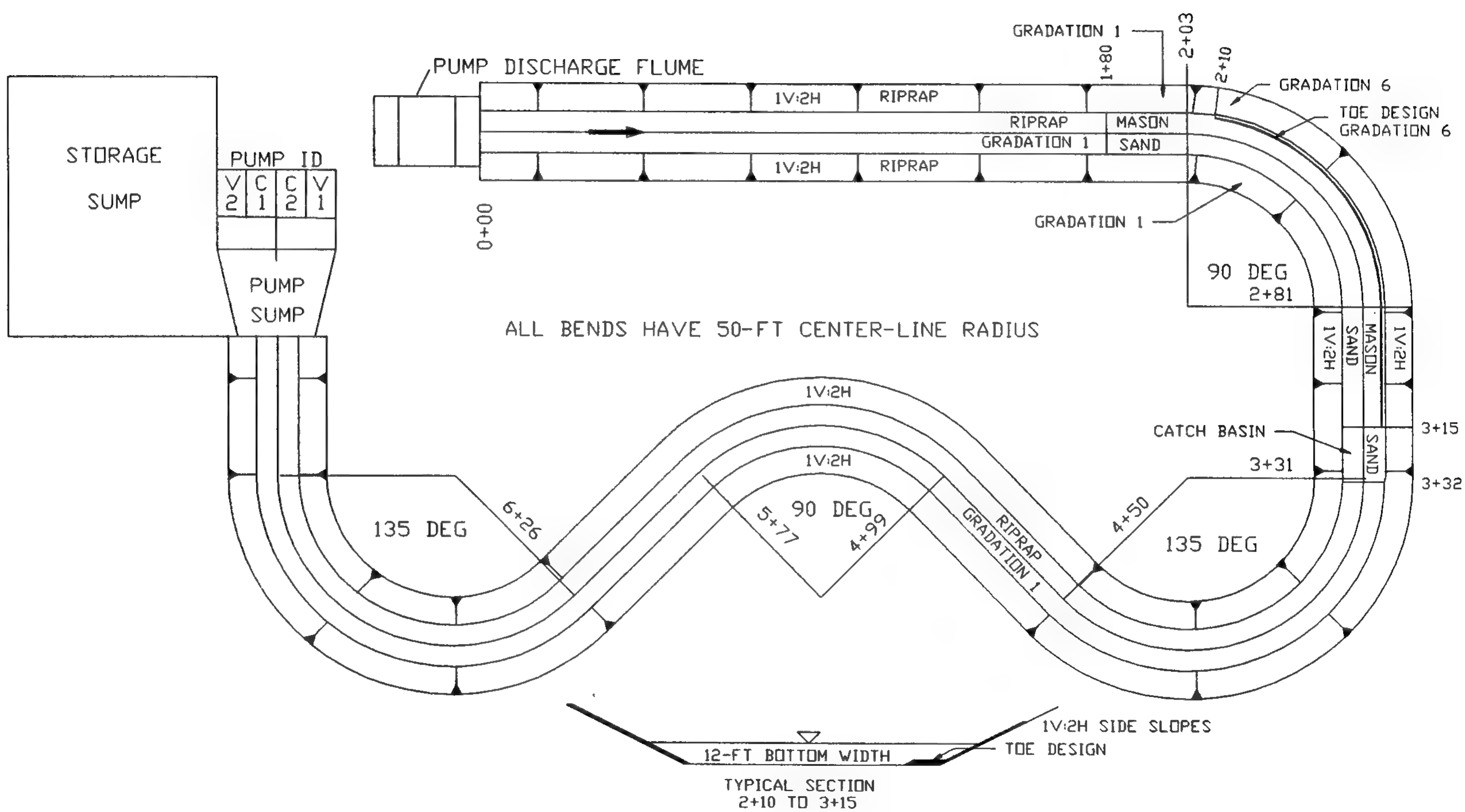
Toe Design No.	Average Failure Depth, ft[1]	Average Launched Slope	Launched Thickness in.[2]
3	0.65	1V:2.1H	0.88
4	0.69	1V:2:05H	0.85
5	0.73	1V:2.7H	0.63
6	0.69	1V:3.1H	0.59
7	0.70	1V:2.45H	0.72
8	0.69	1V:2.45H	0.73
20	0.66	1V:2.3H	0.81
21R1-R2	0.72	1V:2.55H	0.68
21R3	0.69	1V:2.4H	0.74
22	0.75	1V:2.1H	0.76
23	0.65	1V:1.9H	0.96
24	0.71	1V:2.6H	0.67
25	0.76	1V:2.45H	0.66
26	0.72	1V:2.04H	0.82
27	0.70	1V:2.0H	0.85
28	1.09	1V:2.3H	0.73
29	1.15	1V:2.13H	0.74
30	1.19	1V:2.03H	0.74

Notes: Toes 3-27 had an area of 16 sq in.
Toes 28-30 had an area of 24 sq in.
Required bank protection thickness T = 1 in.

[1] Average failure depth (AFD) is average of upstream and downstream failure depth and the average of the initial (R1) and repeat (R2) tests.

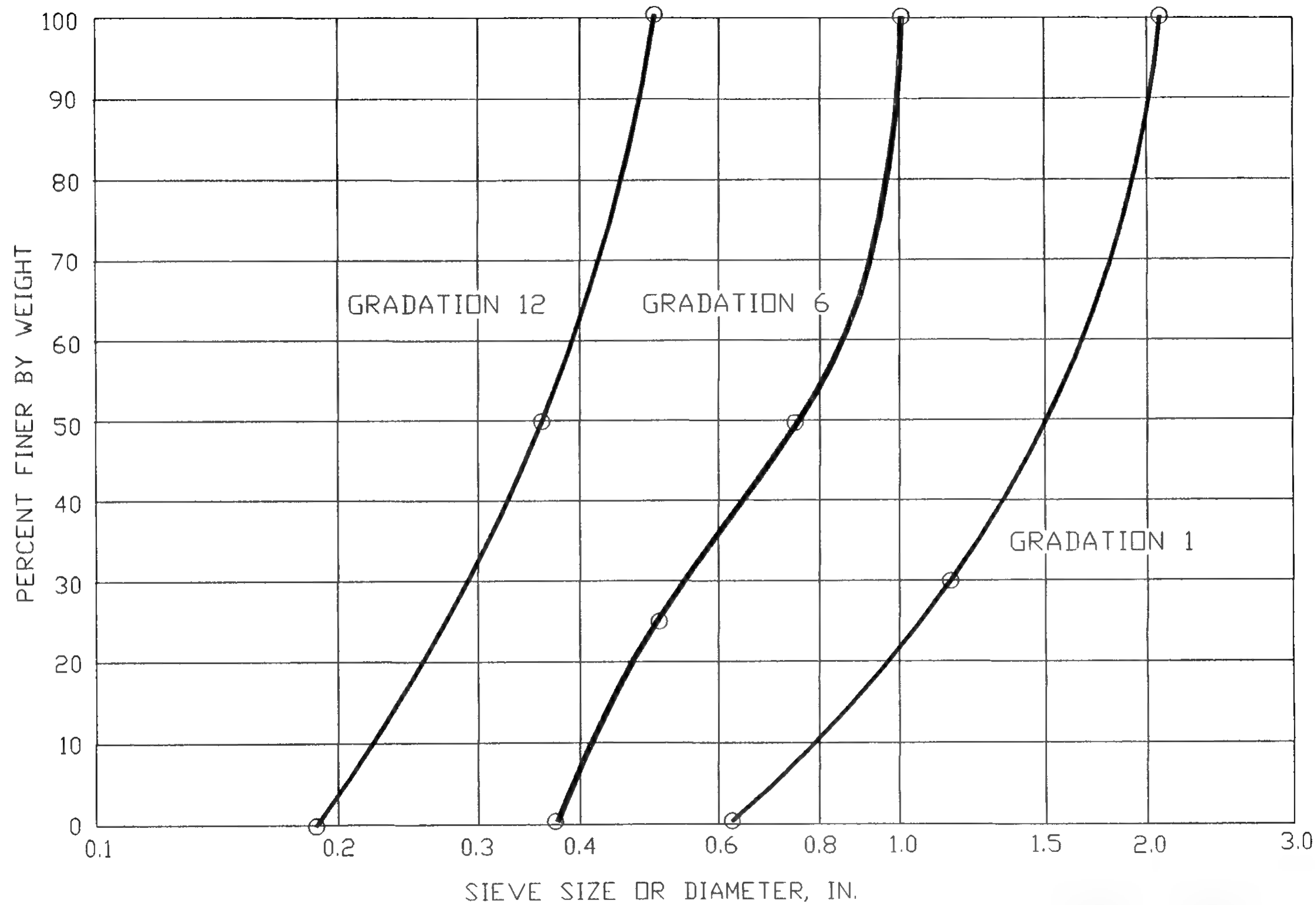
[2] Launched thickness is calculated by $\dfrac{\textit{Toe Area}}{\textit{Launched Slope Length}}$

Launched slope length = $AFD(A^2 + B^2)^{0.5}$ where A and B are found from average slope as AV:BH.

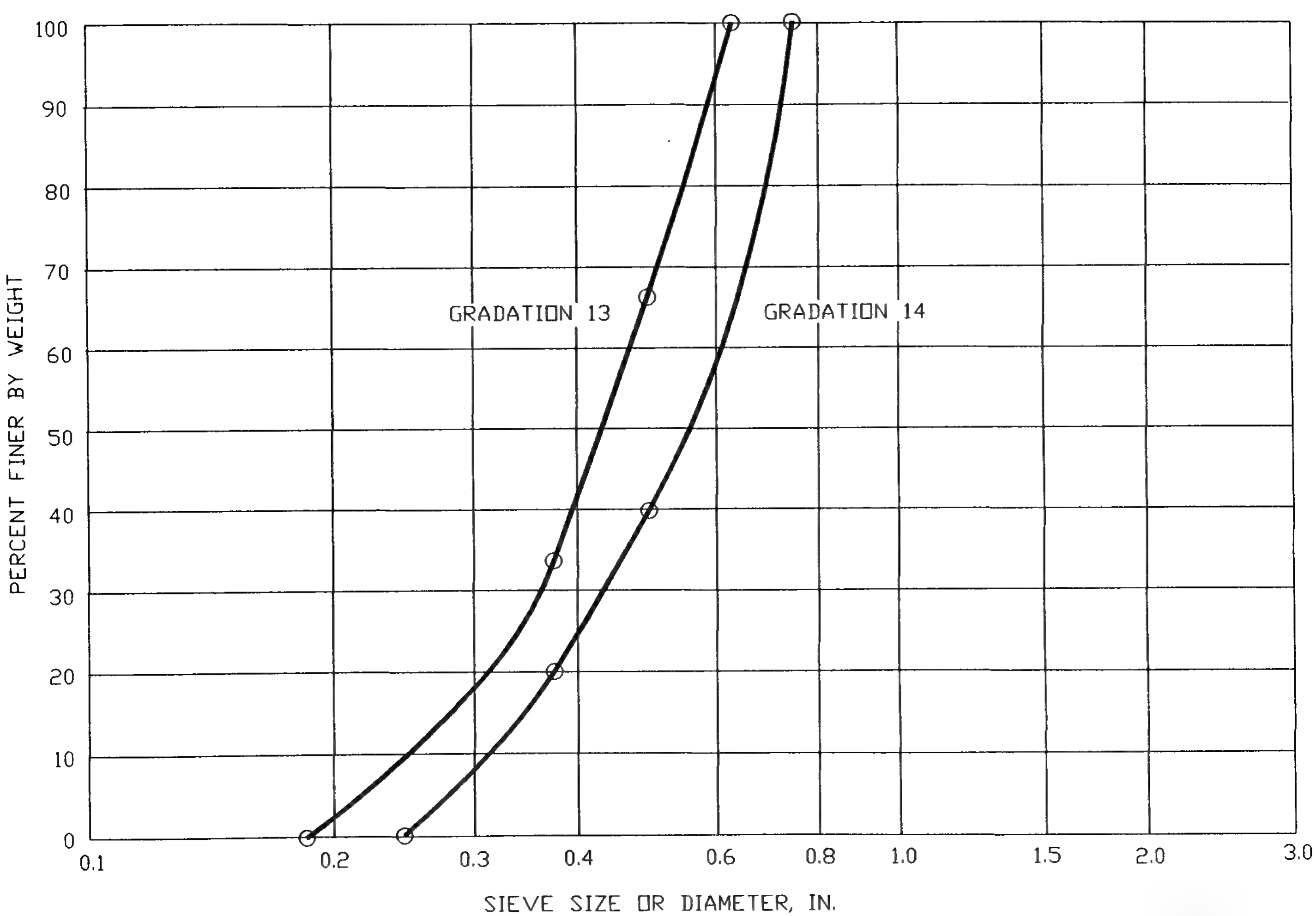


NOTES:
1. CHANNEL SIDE SLOPE WAS 1V:1.5H ON TESTS 3 THROUGH 8
2. TOE DESIGN VARIED IN SHAPE FROM TEST TO TEST
3. GRADATION CHANGED ON TOE DESIGNS 7, 8, 26, AND 27

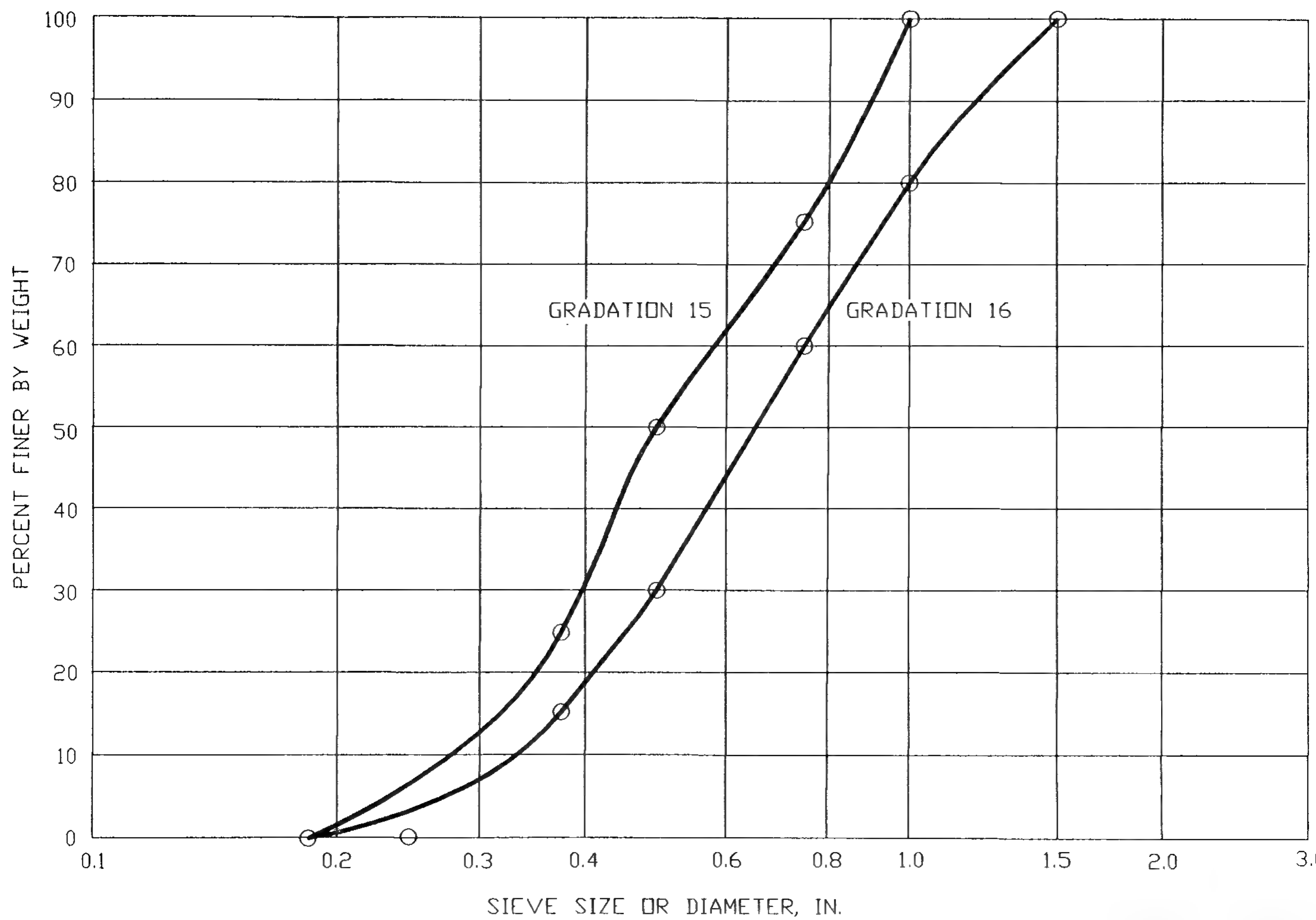
RIPRAP TEST FACILITY



GRADATIONS 1, 6, AND 12

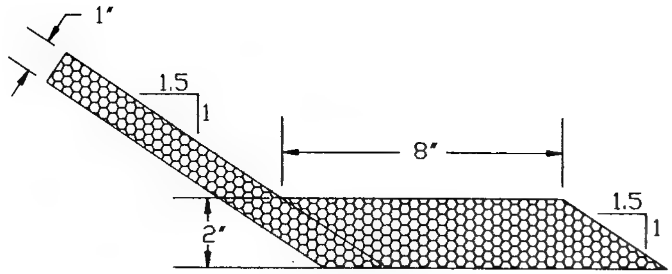


GRADATIONS 13 AND 14

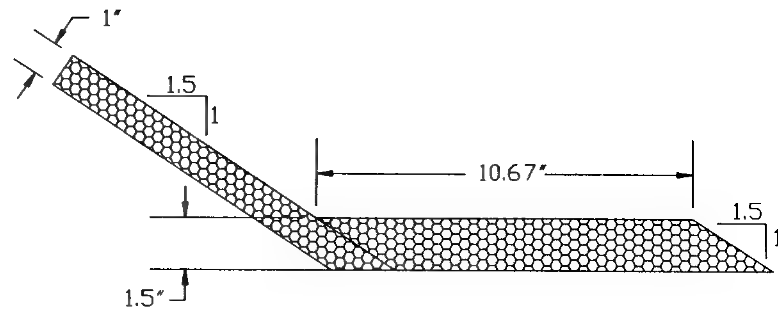


GRADATIONS 15 AND 16

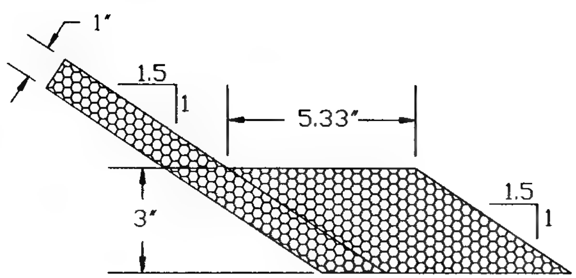
Plate 4



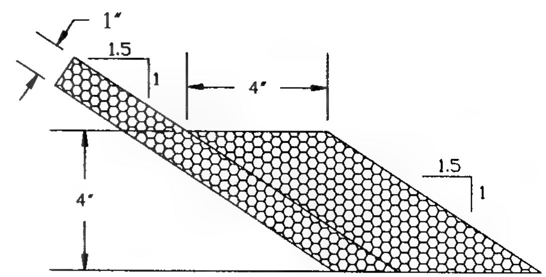
TOE DESIGN 5



TOE DESIGN 6



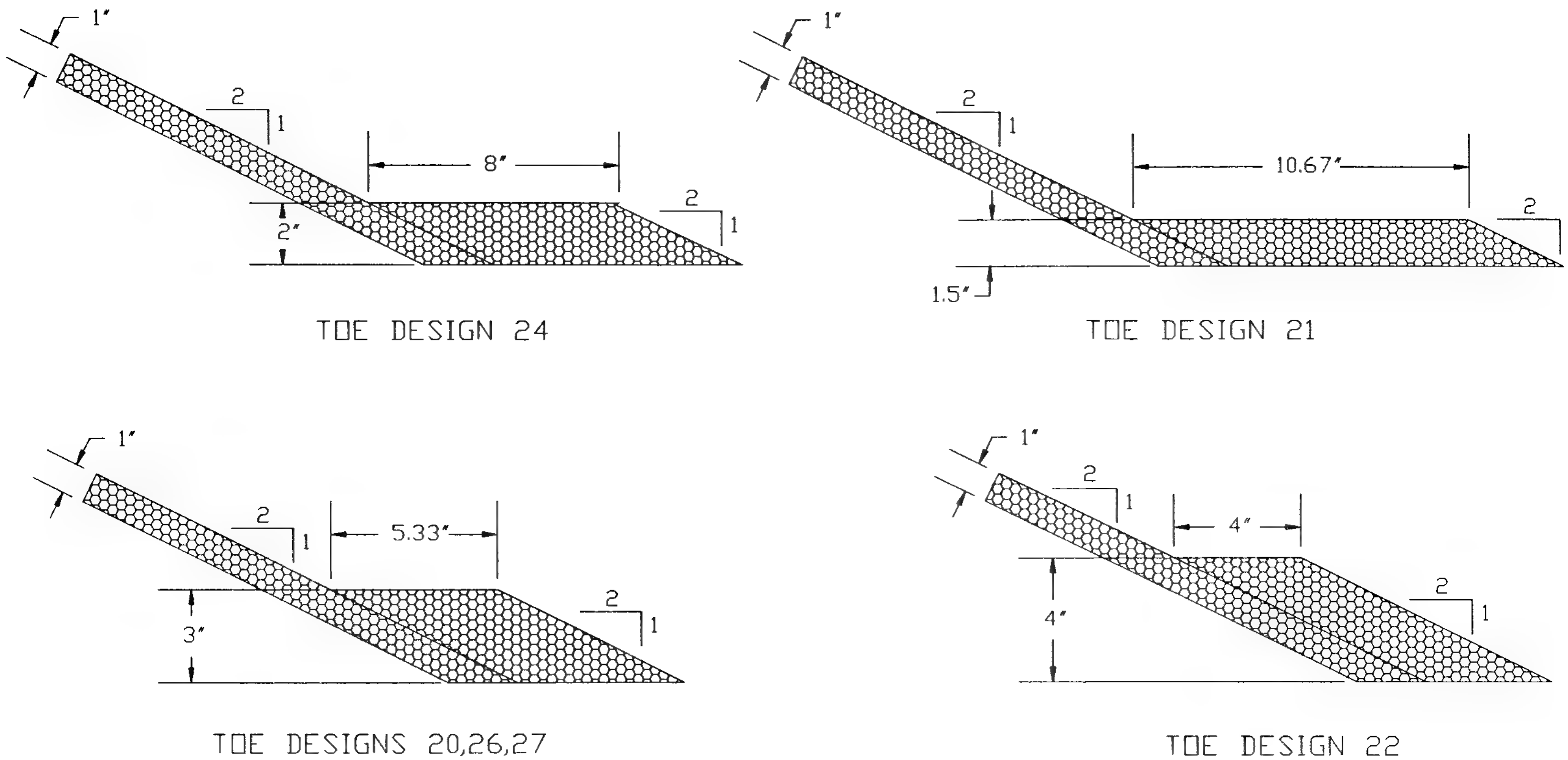
TOE DESIGNS 3,7,8



TOE DESIGN 4

TOE DESIGNS 3-8

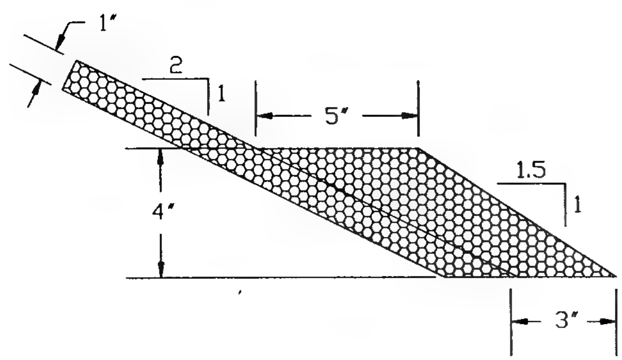
SIDE SLOPE 1V:1.5H



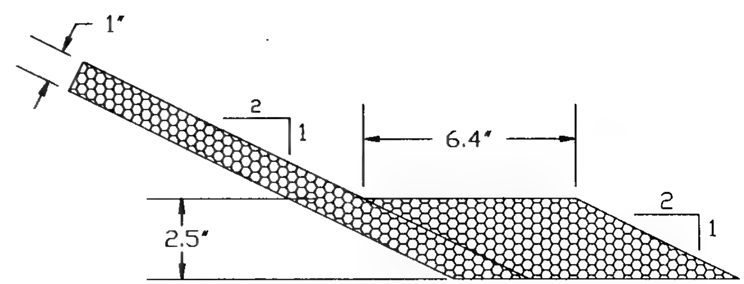
TOE DESIGNS 20-22,24,26-27

SIDE SLOPE 1V:2H

Plate 6



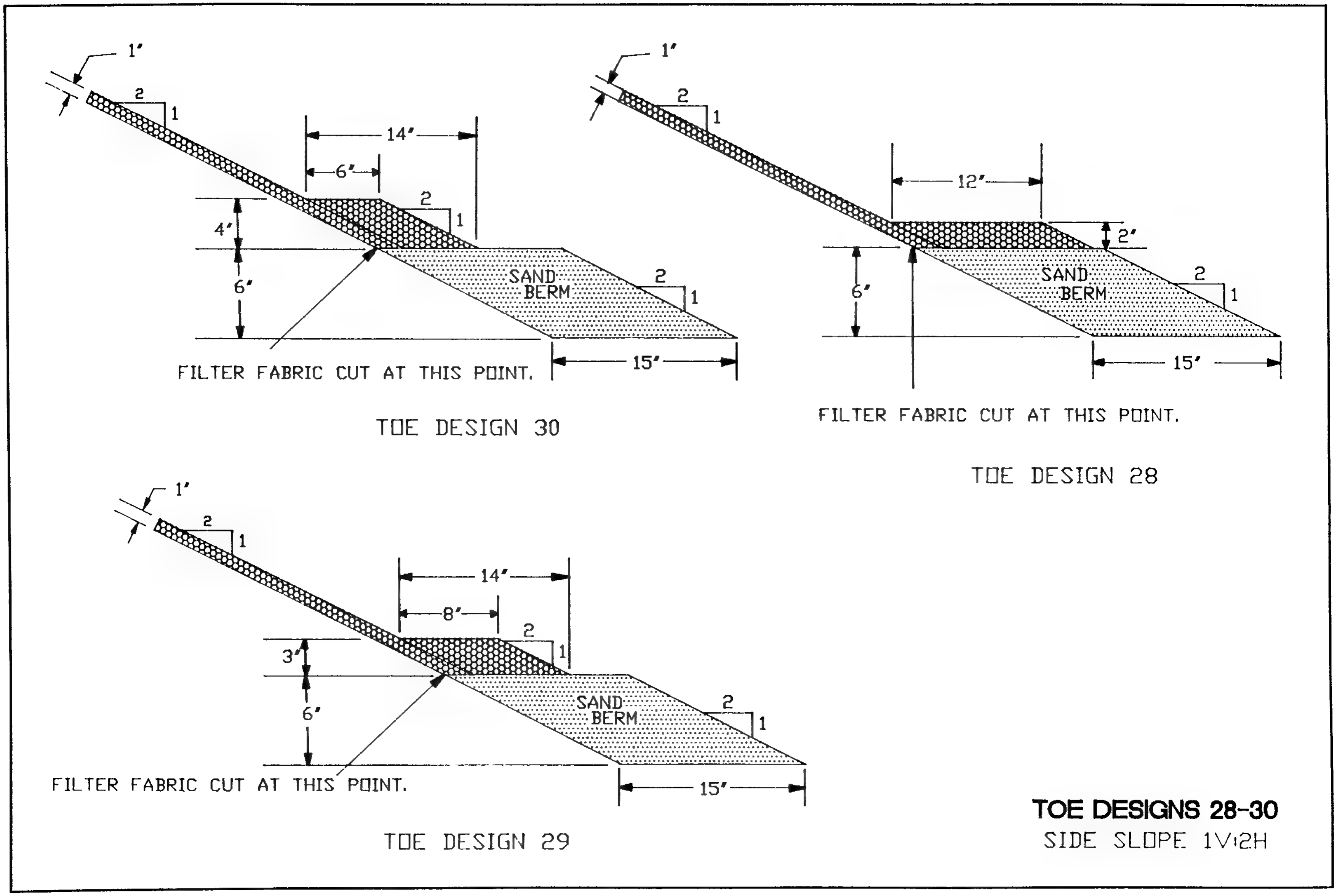
TOE DESIGN 23

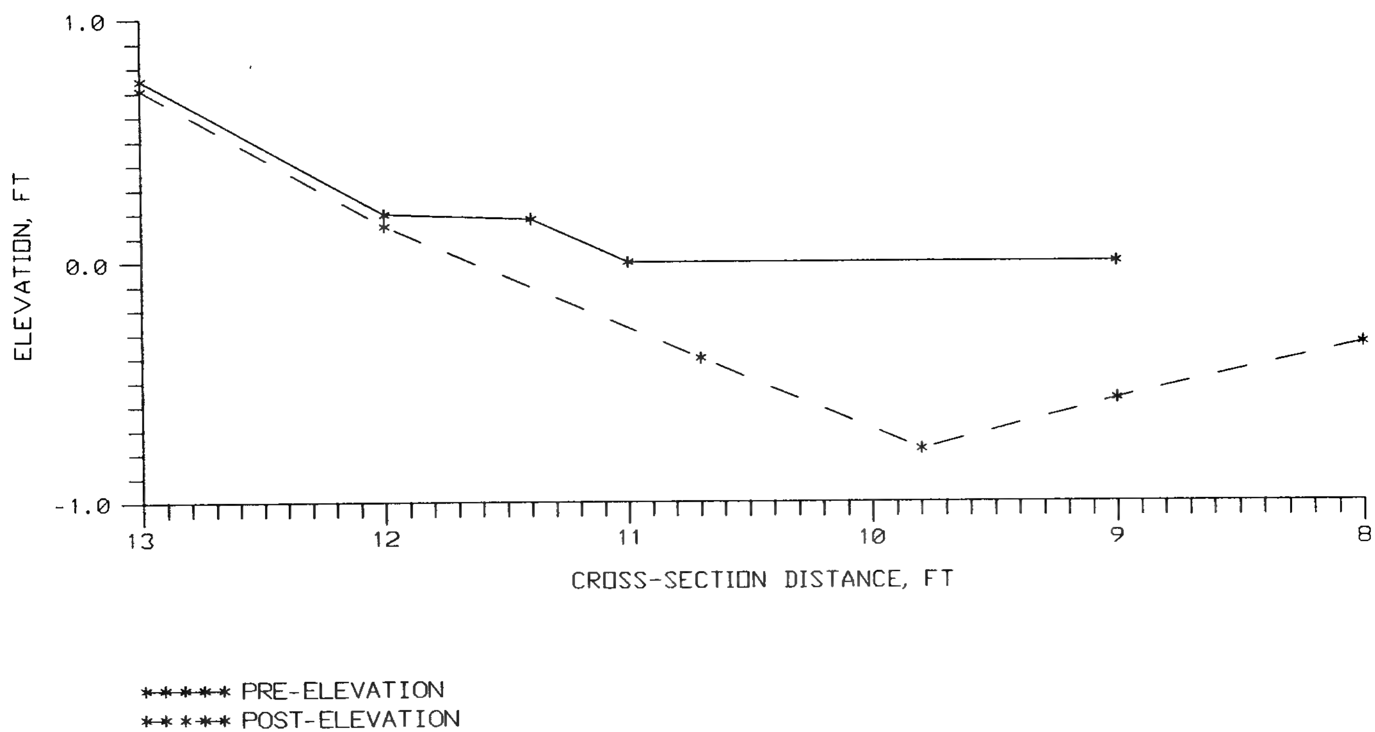


TOE DESIGN 25

TOE DESIGNS 23,25

SIDE SLOPE 1V:2H


1'
2
1
14'
6'
4'
6'
SAND BERM
FILTER FABRIC CUT AT THIS POINT.
15'
TOE DESIGN 30
12'
2'
FILTER FABRIC CUT AT THIS POINT.
TOE DESIGN 28
8'
3'
FILTER FABRIC CUT AT THIS POINT.
TOE DESIGN 29
TOE DESIGNS 28-30
SIDE SLOPE 1V:2H

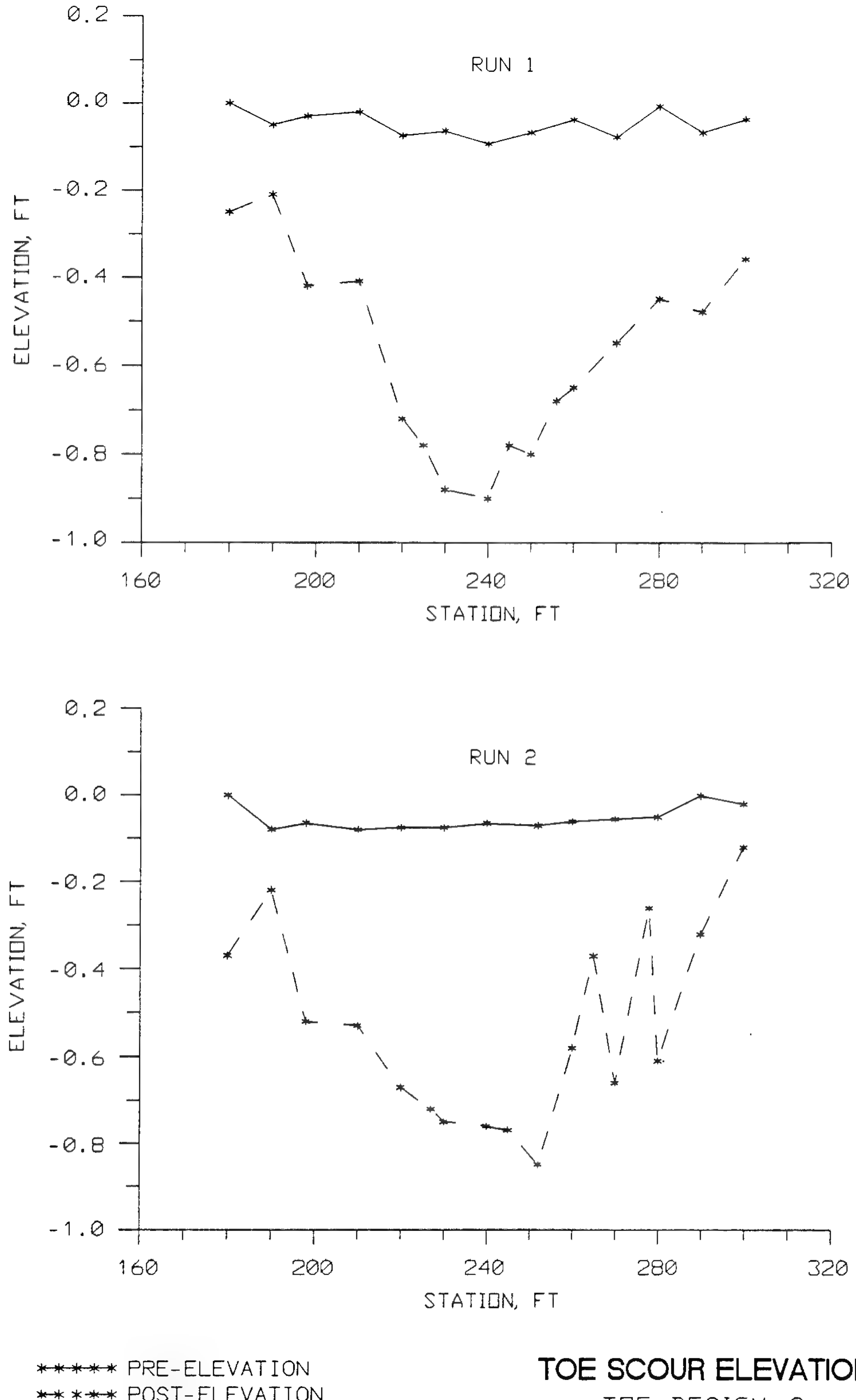


TOE SCOUR CROSS SECTION

TOE DESIGN 24

RUN 1

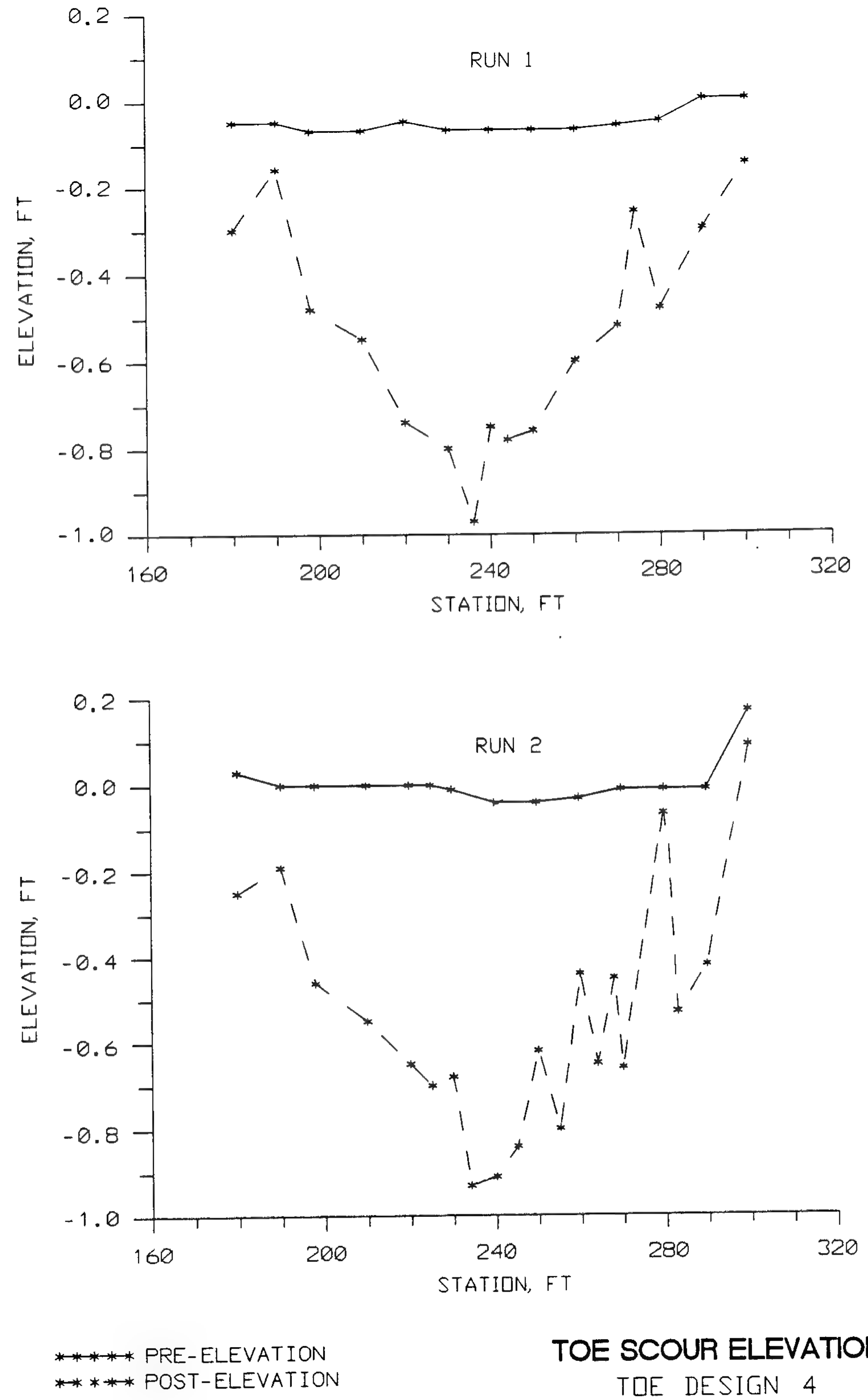
STATION 250



TOE SCOUR ELEVATION

TOE DESIGN 3

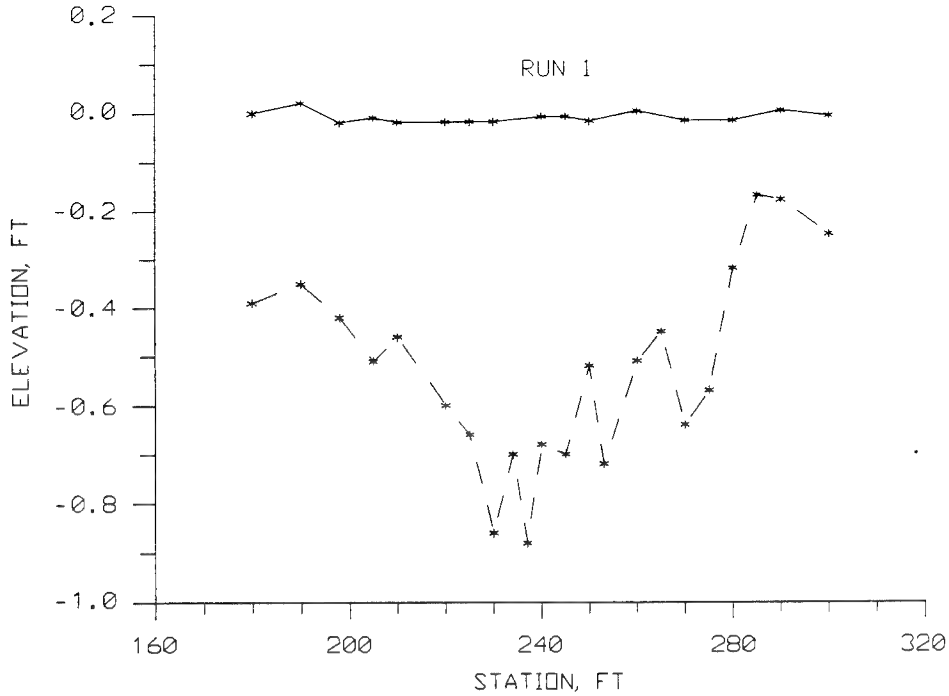
RUNS 1 AND 2

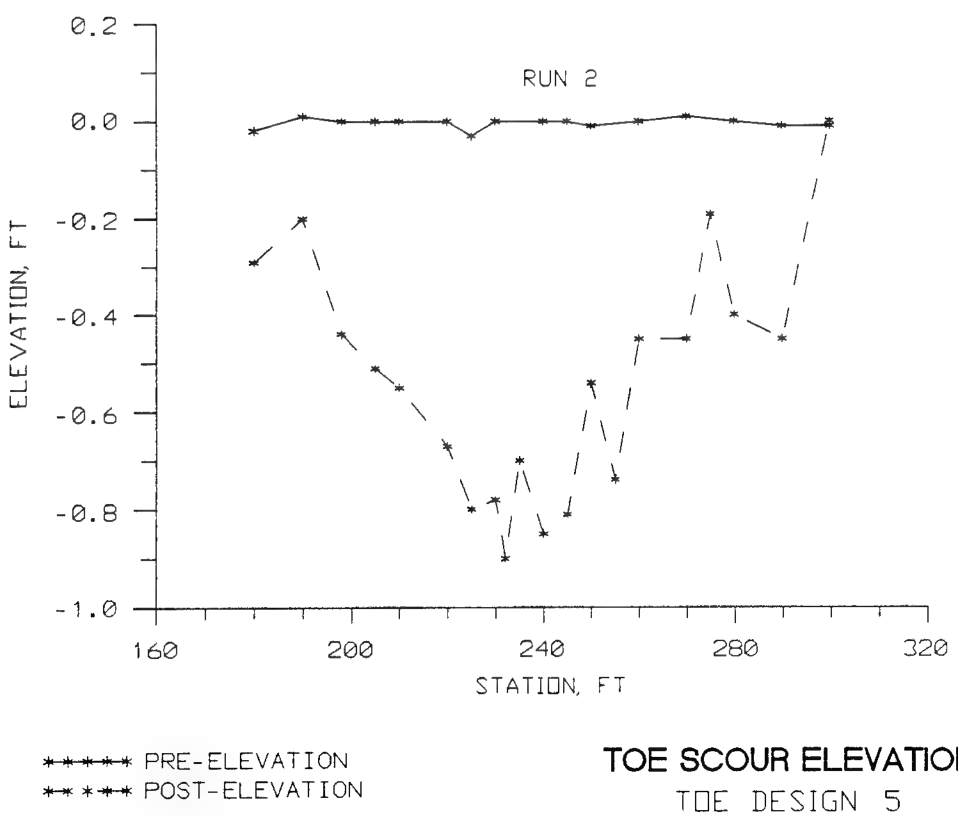


TOE SCOUR ELEVATION

TOE DESIGN 4

RUNS 1 AND 2



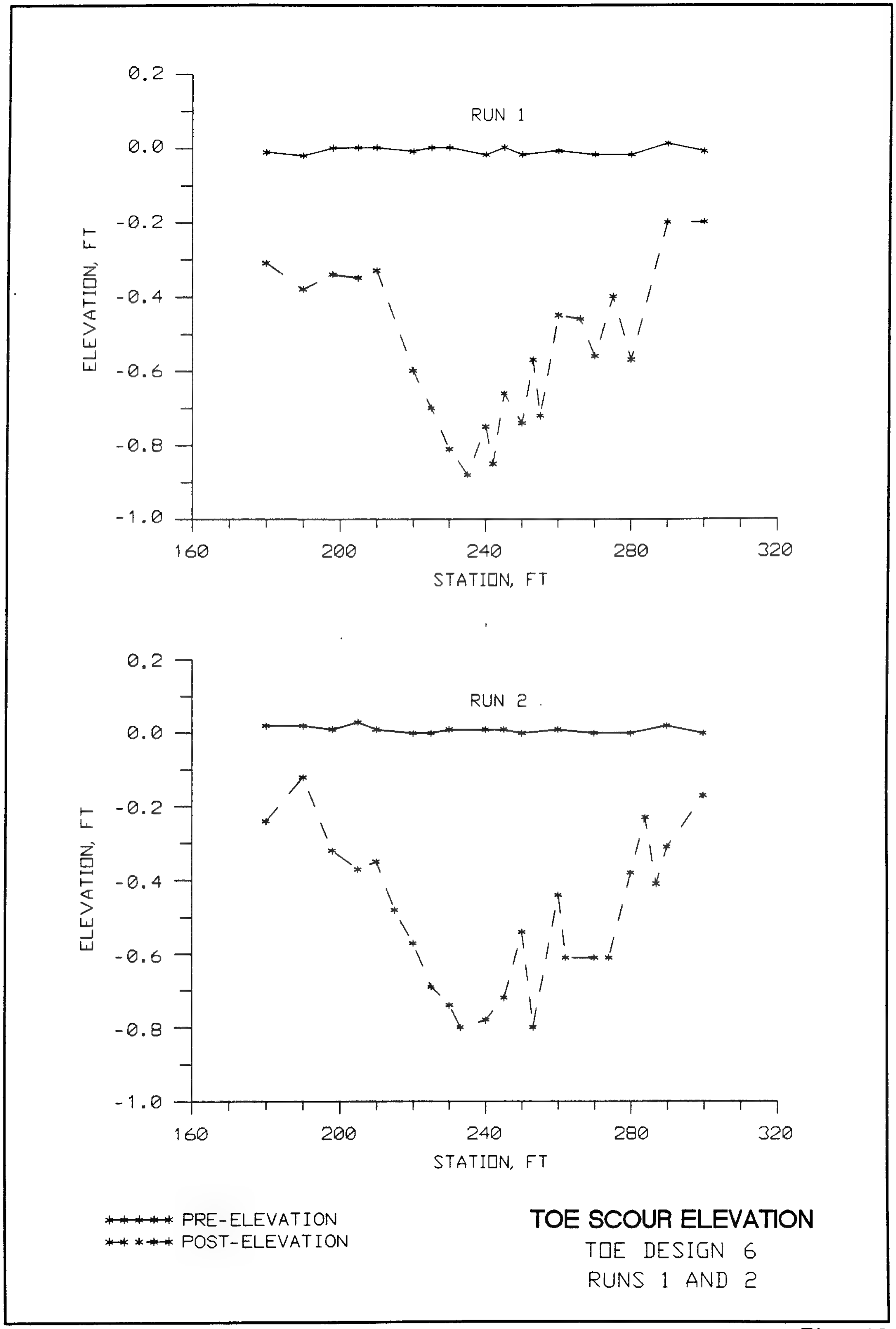


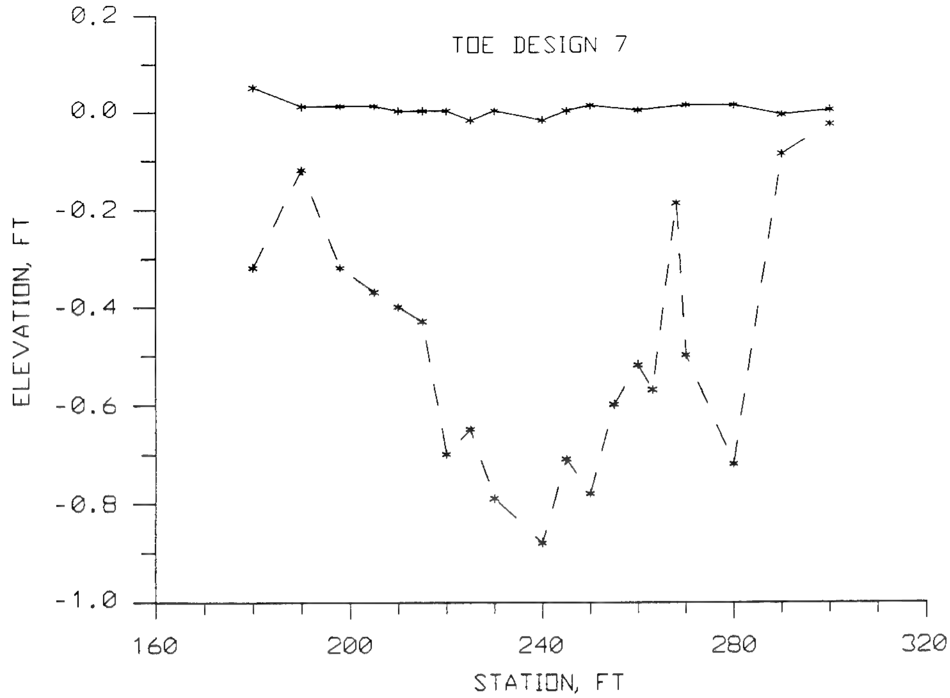
TOE SCOUR ELEVATION

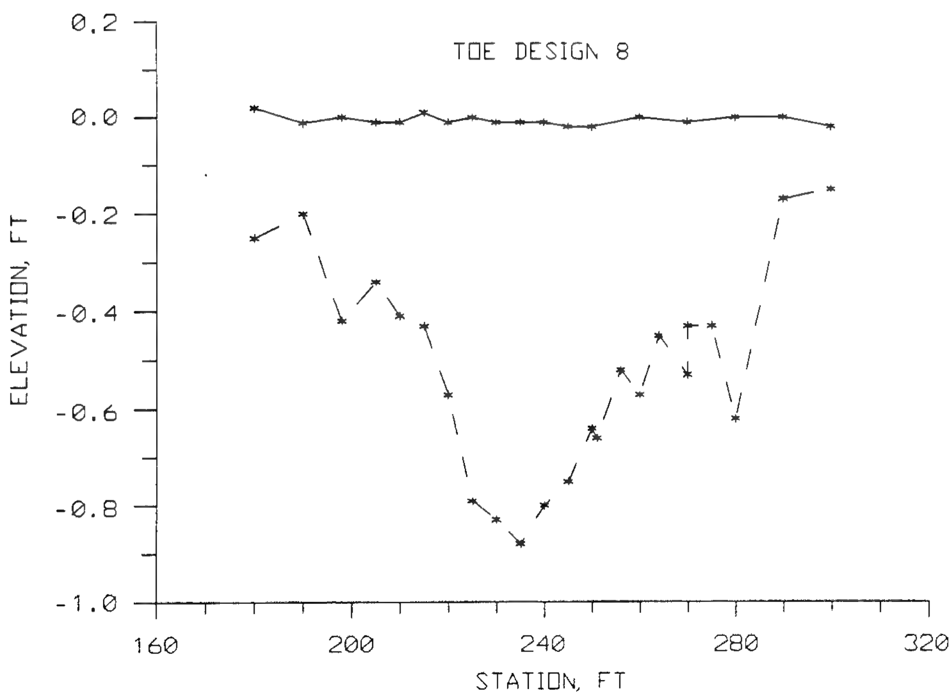
TOE DESIGN 5

RUNS 1 AND 2

Plate 12


RUN 1
ELEVATION, FT
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
160
200
240
280
320
STATION, FT
RUN 2
ELEVATION, FT
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
160
200
240
280
320
STATION, FT
PRE-ELEVATION
POST-ELEVATION
TOE SCOUR ELEVATION
TOE DESIGN 6
RUNS 1 AND 2



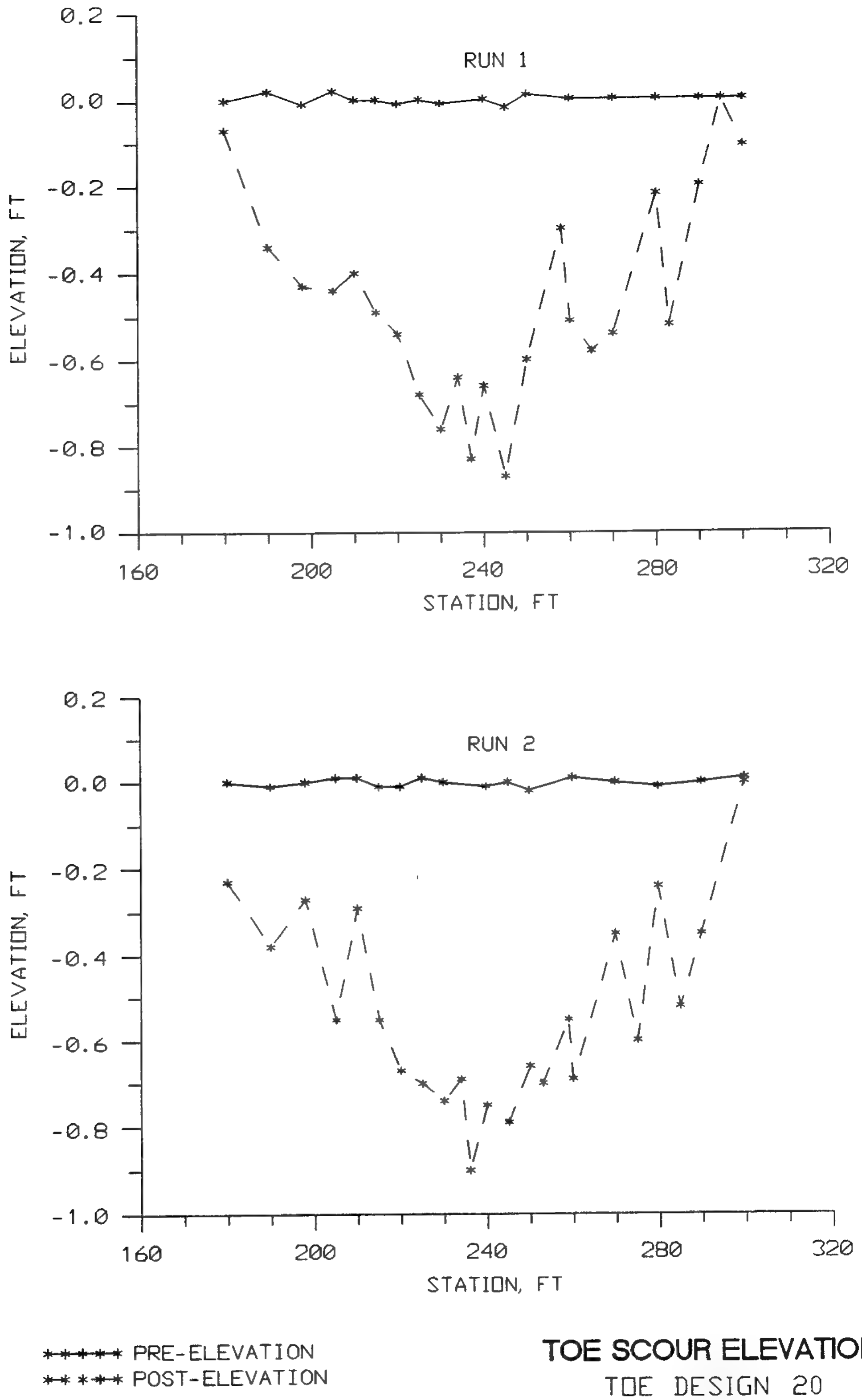


PRE-ELEVATION
POST-ELEVATION

TOE SCOUR ELEVATION

TOE DESIGNS 7 AND 8

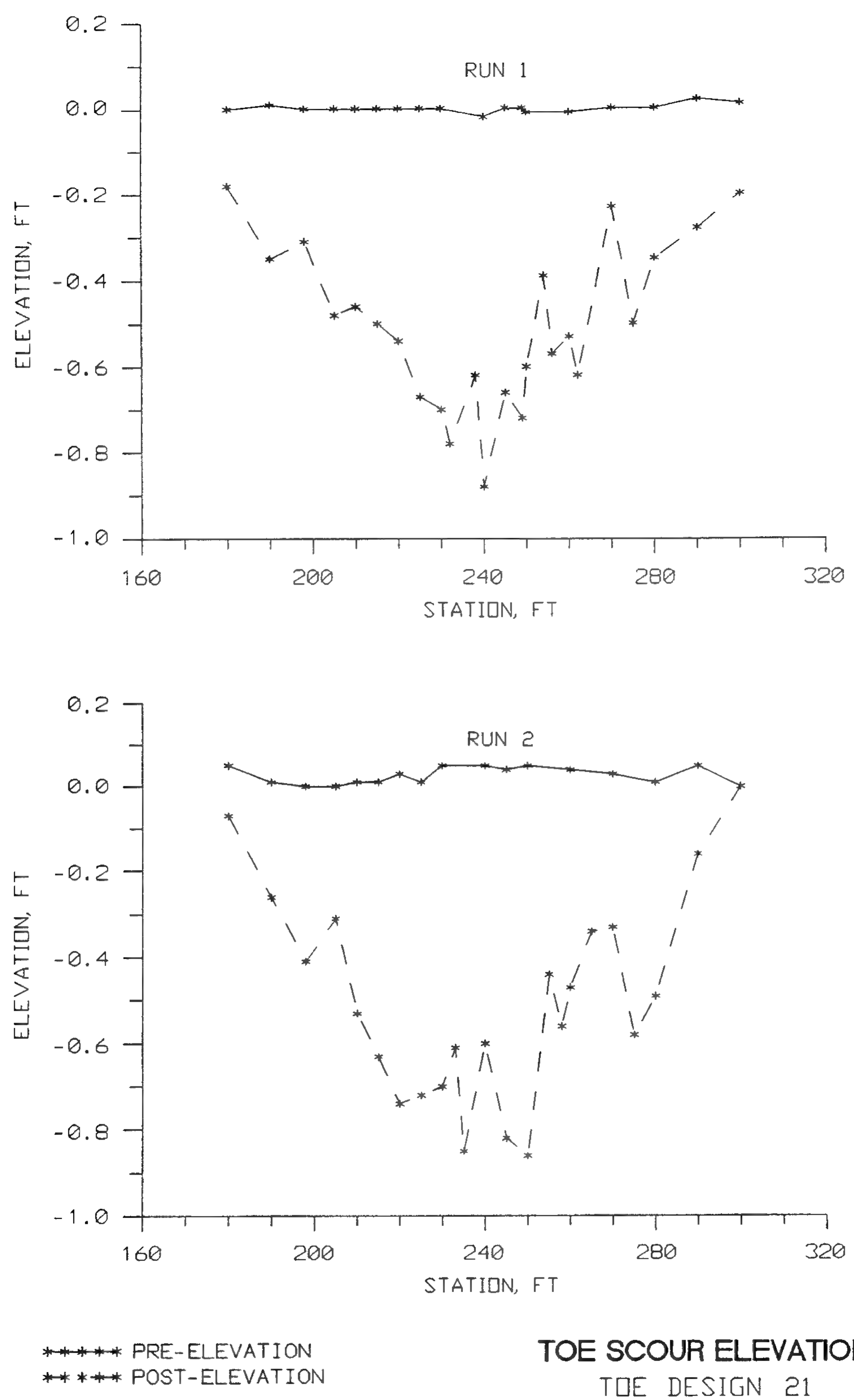
RUN 1



TOE SCOUR ELEVATION

TOE DESIGN 20

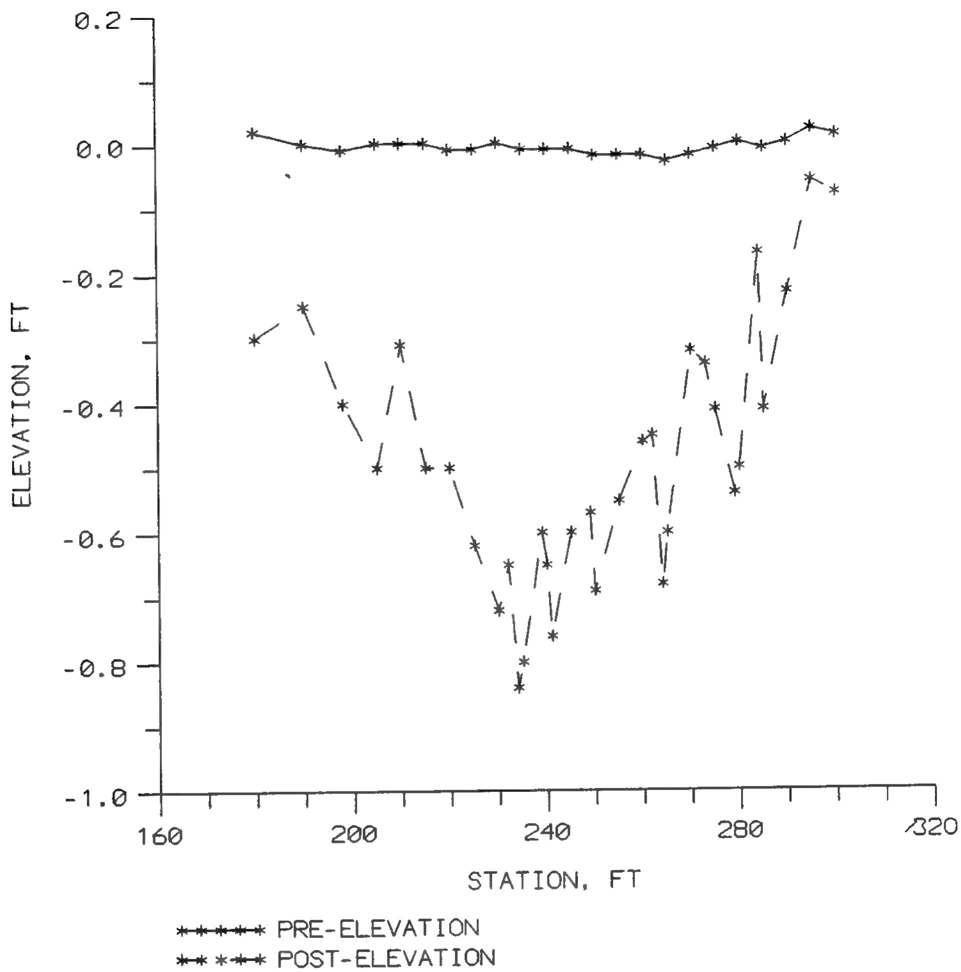
RUNS 1 AND 2



TOE SCOUR ELEVATION

TOE DESIGN 21

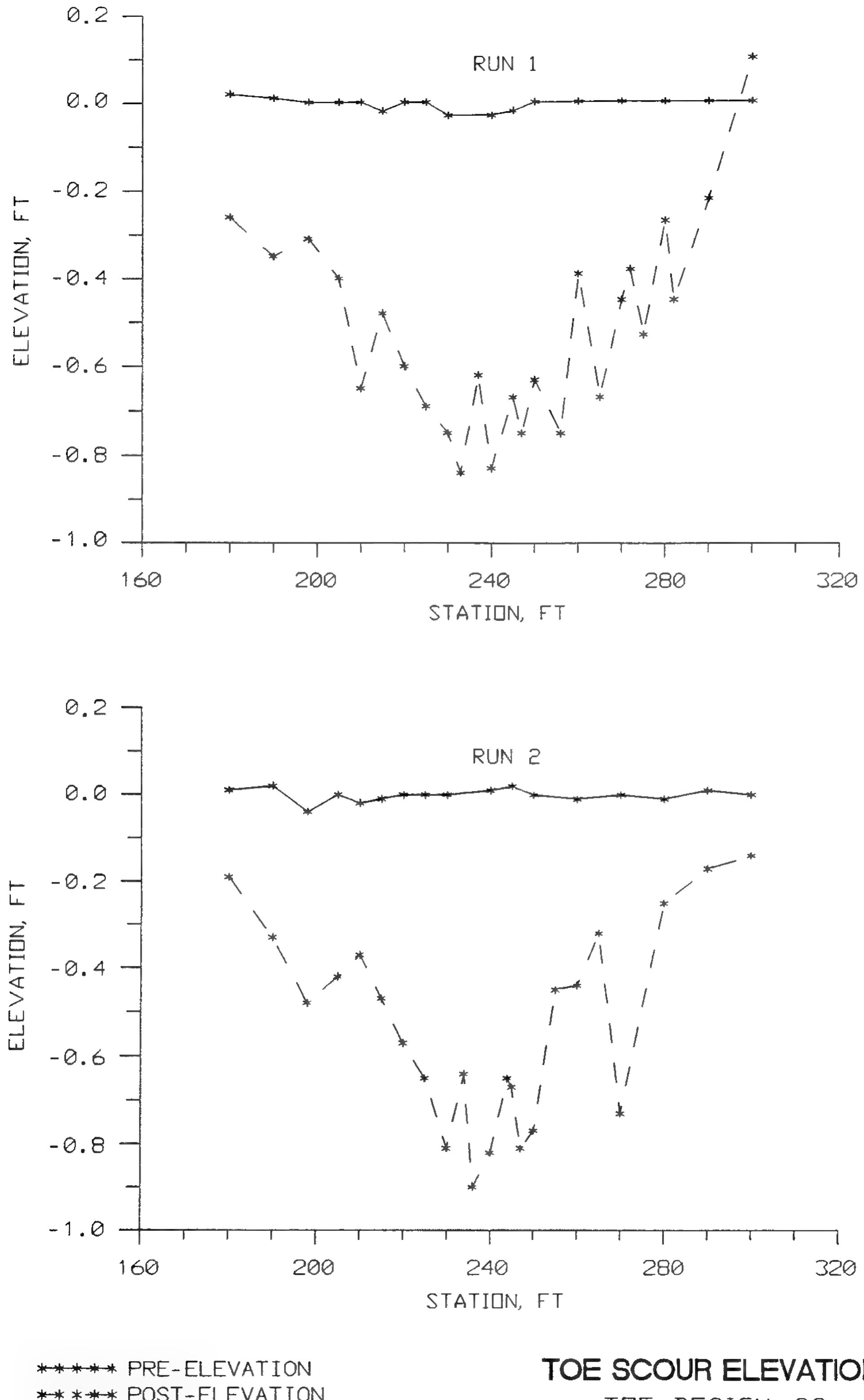
RUNS 1 AND 2



TOE SCOUR ELEVATION

TOE DESIGN 21

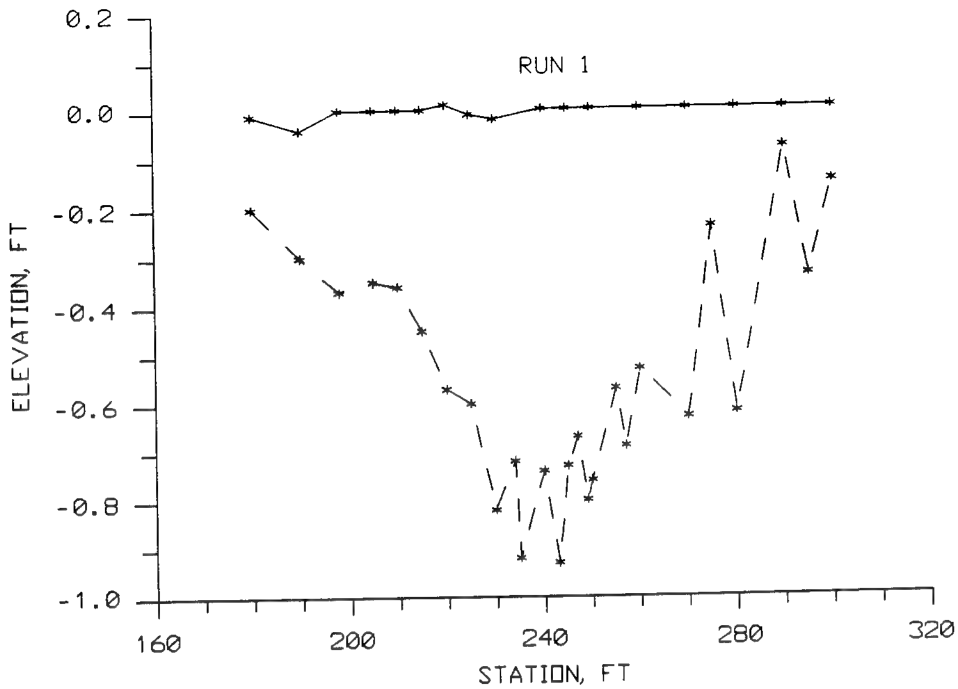
RUN 3

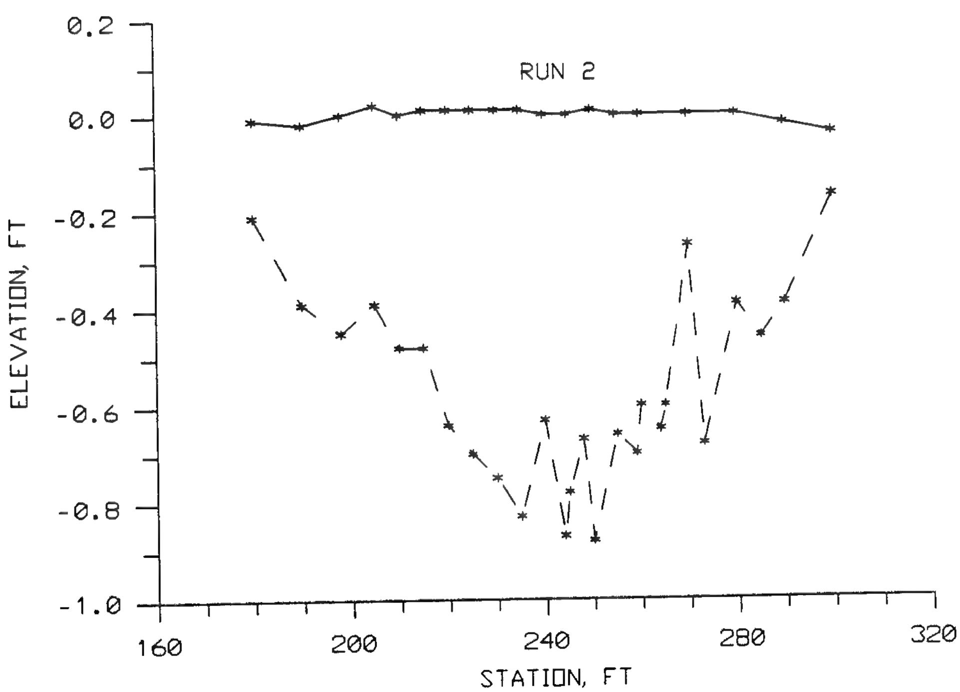


TOE SCOUR ELEVATION

TOE DESIGN 22

RUNS 1 AND 2



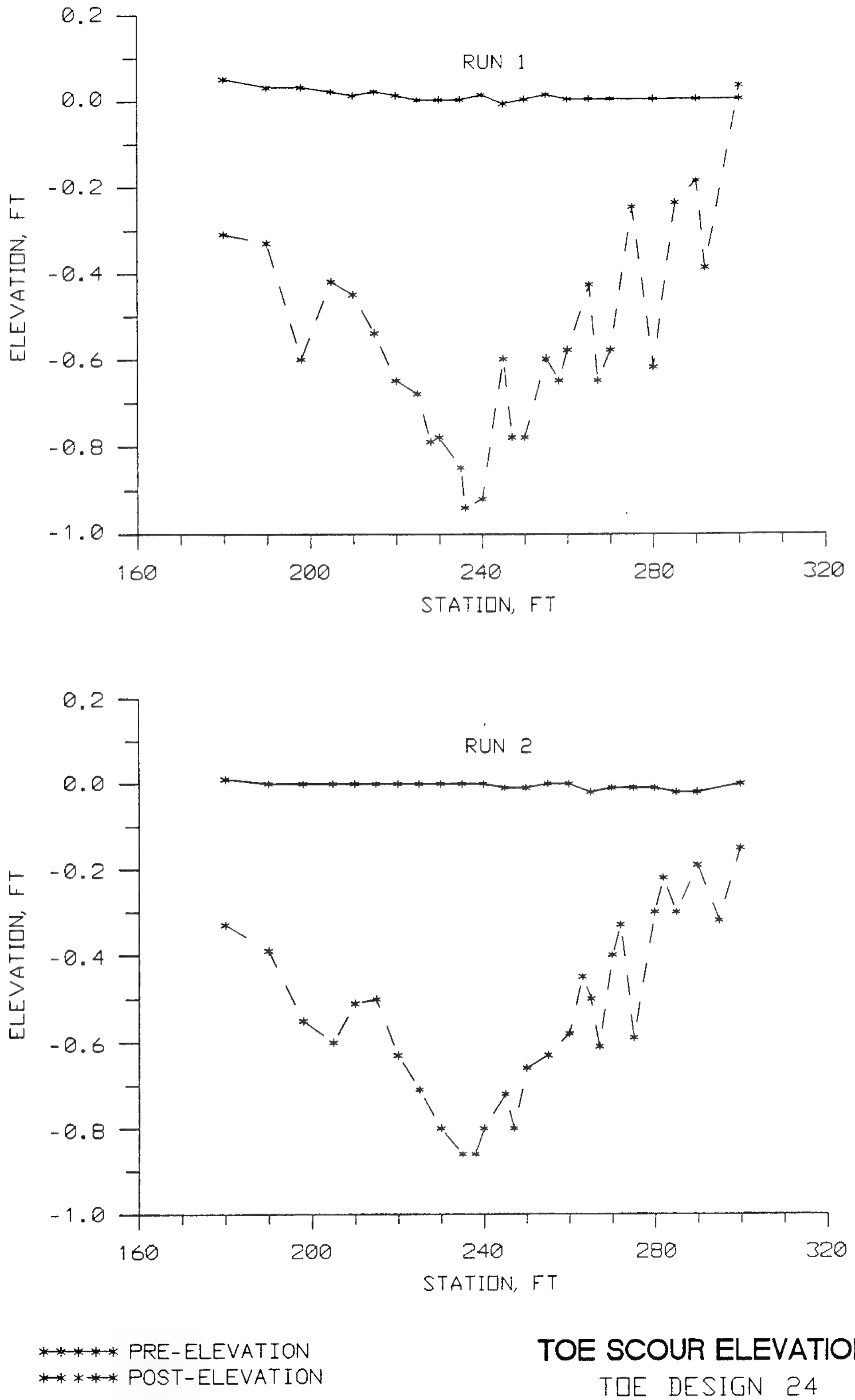


✱✱✱✱✱ PRE-ELEVATION
✱✱ ✱✱✱ POST-ELEVATION

TOE SCOUR ELEVATION

TOE DESIGN 23

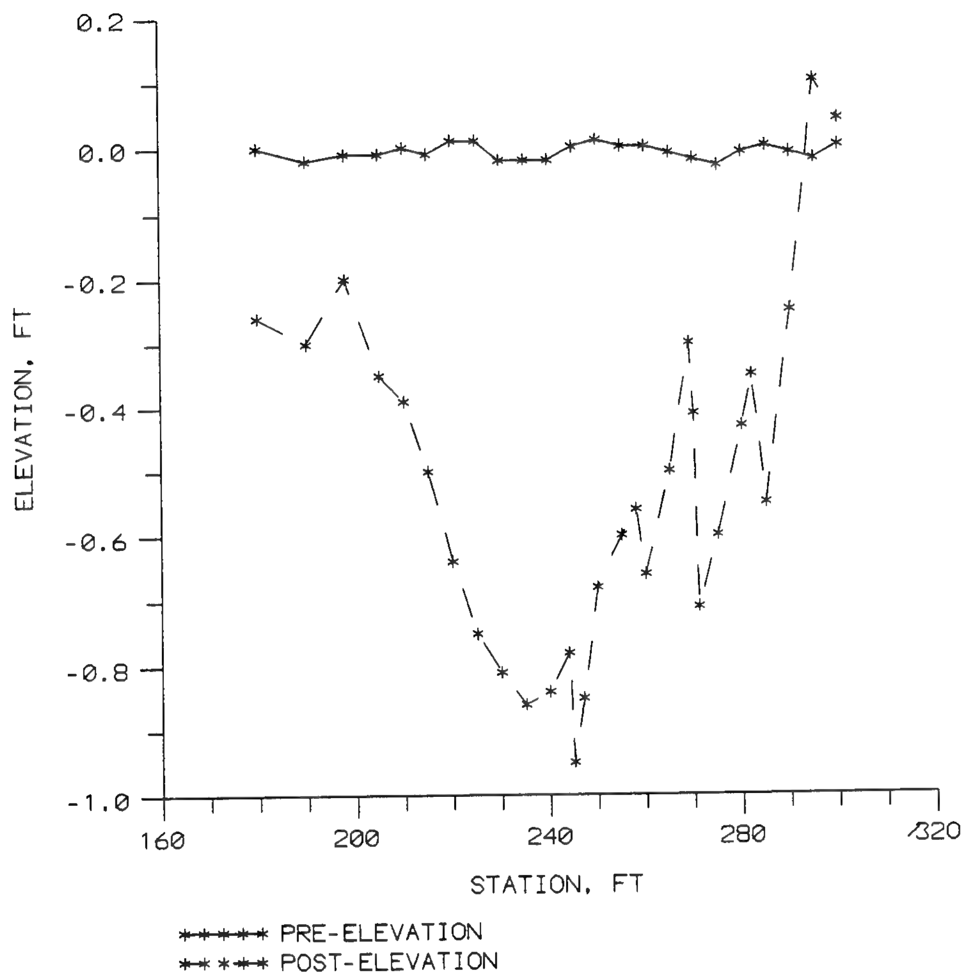
RUNS 1 AND 2



TOE SCOUR ELEVATION

TOE DESIGN 24

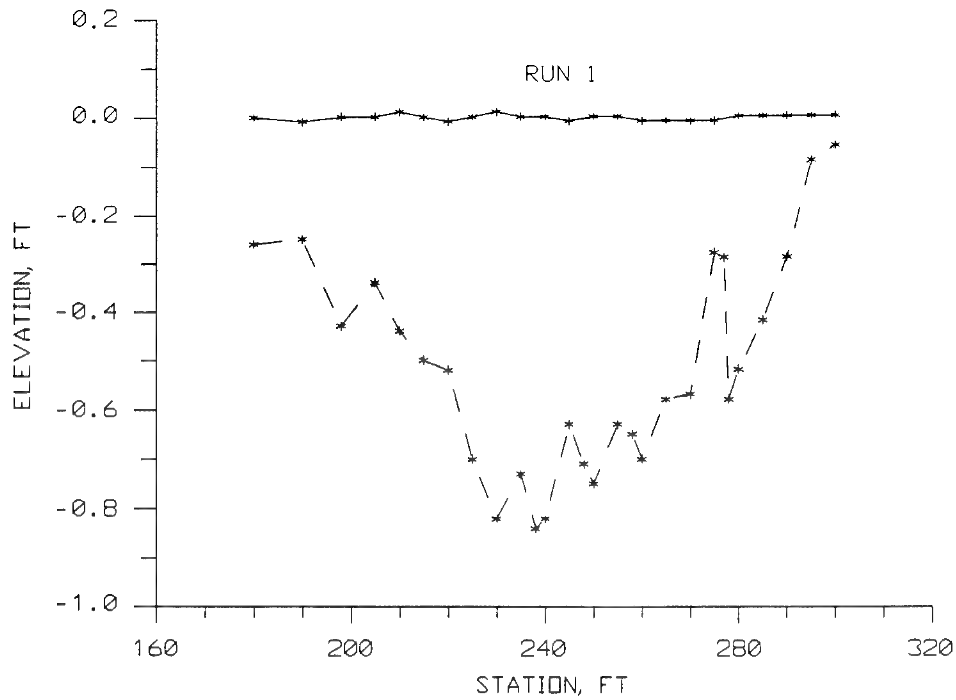
RUNS 1 AND 2

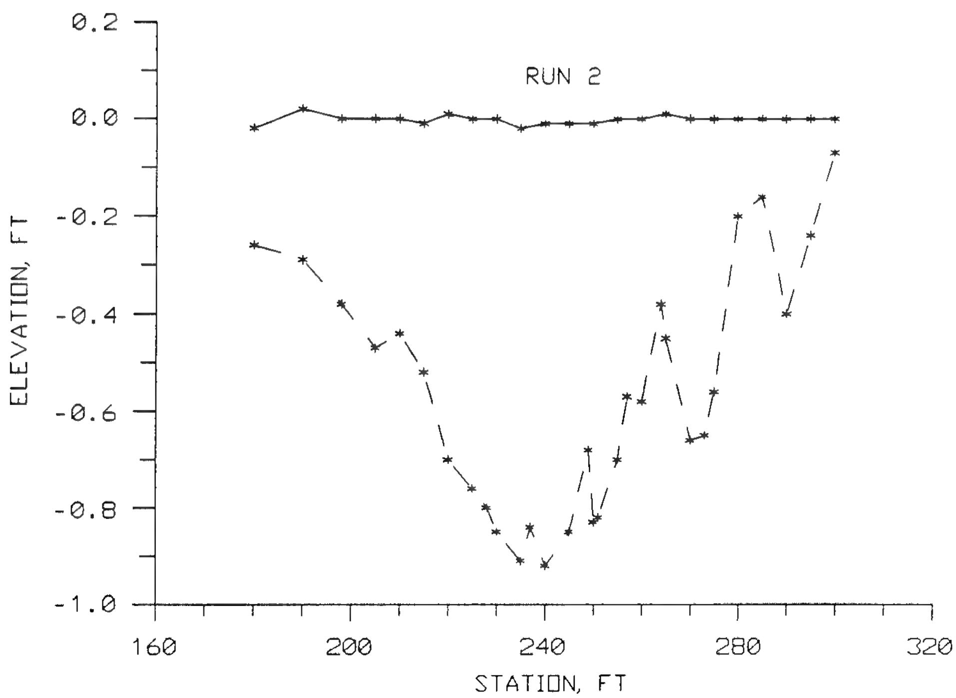


TOE SCOUR ELEVATION

TOE DESIGN 25

RUN 1

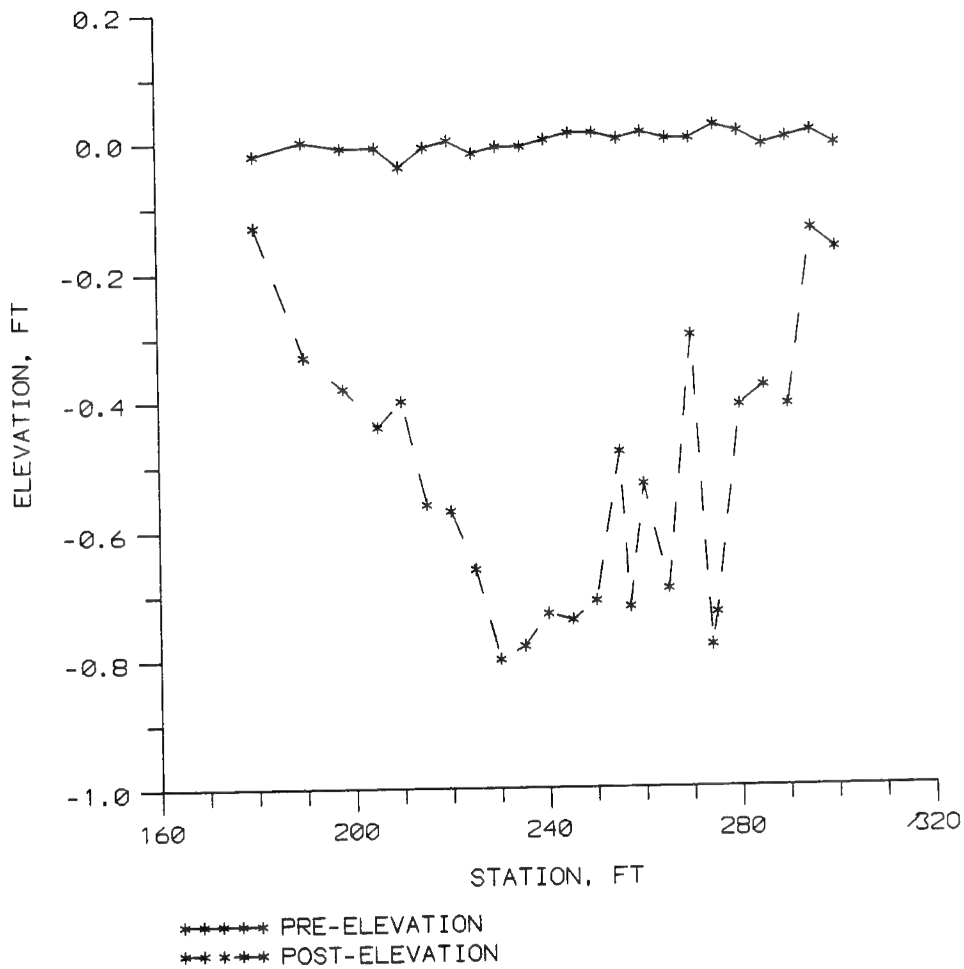




TOE SCOUR ELEVATION

TOE DESIGN 26

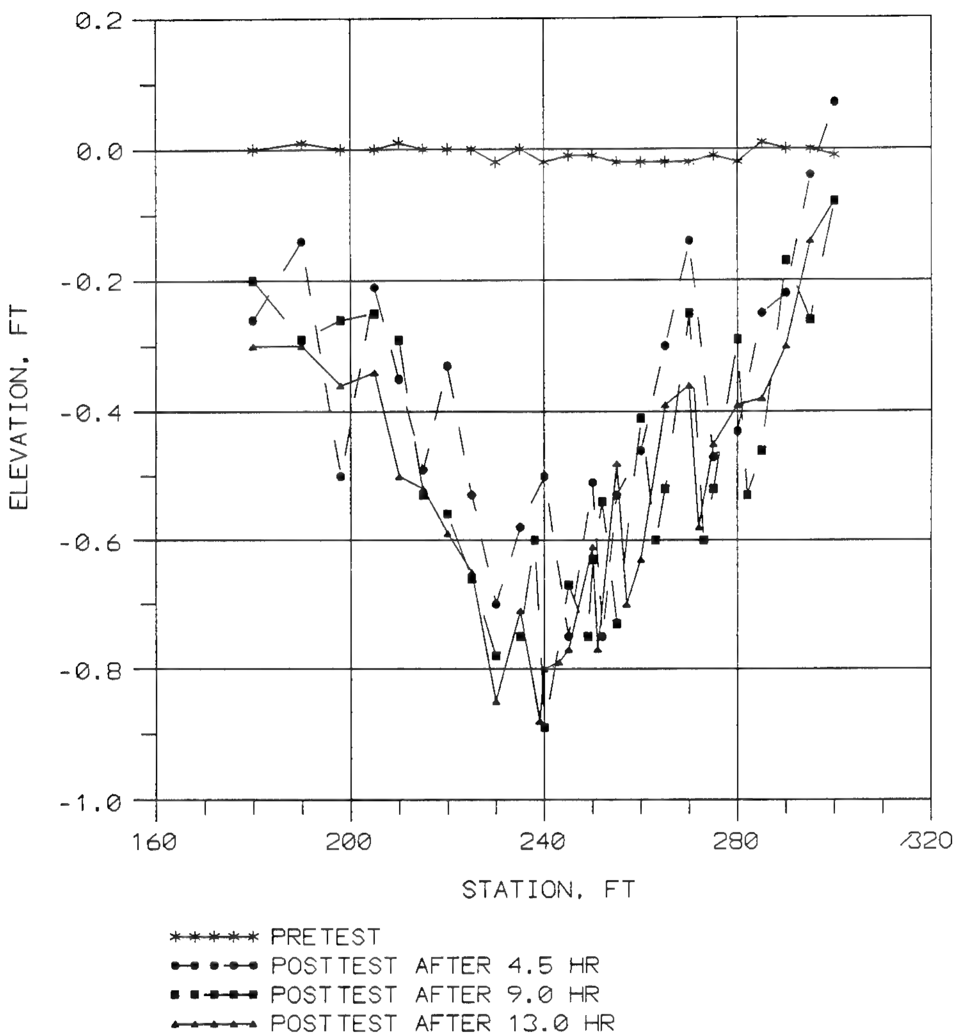
RUNS 1 AND 2



TOE SCOUR ELEVATION

TOE DESIGN 27

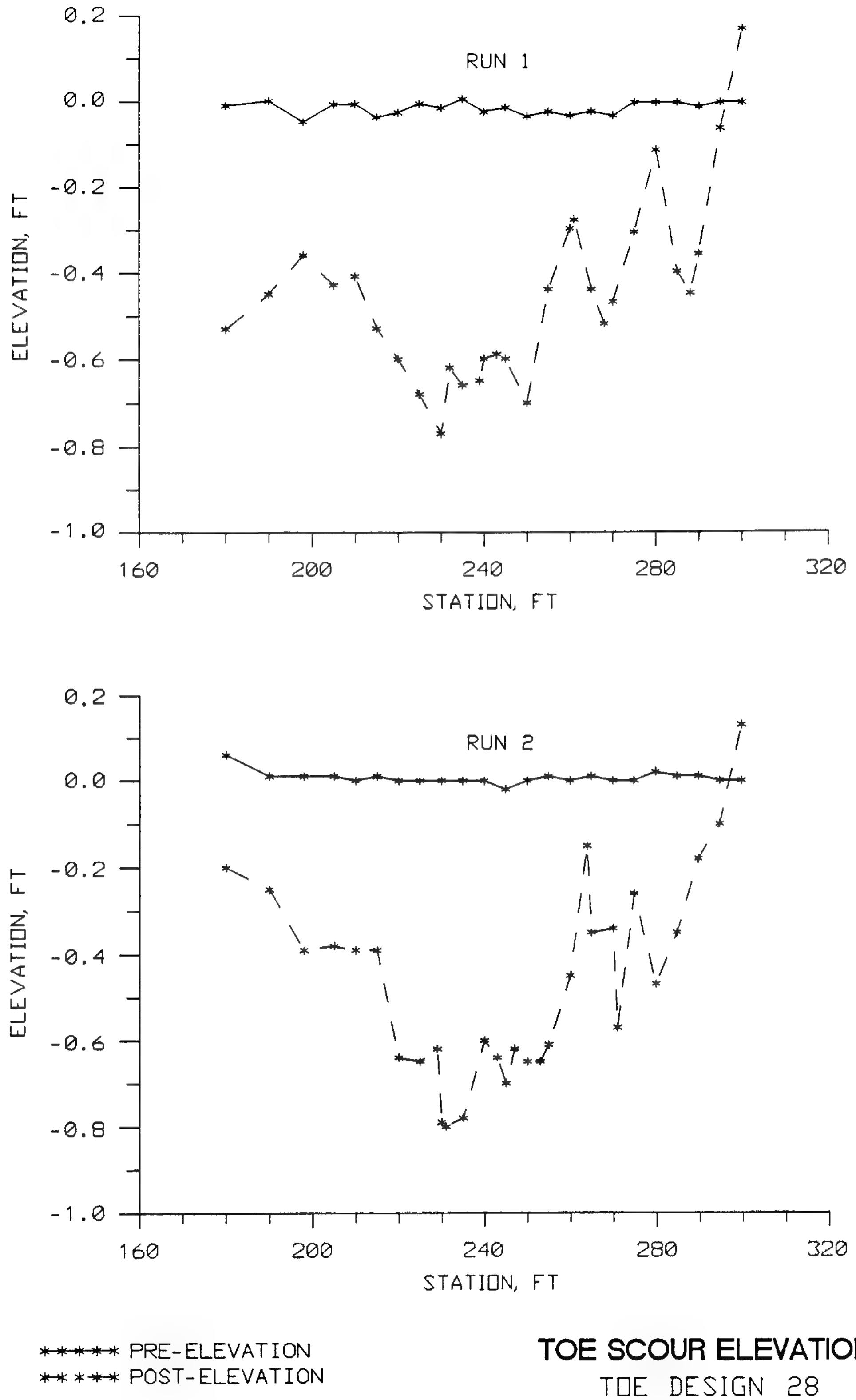
RUN 1



TOE SCOUR ELEVATION

TOE DESIGN 27

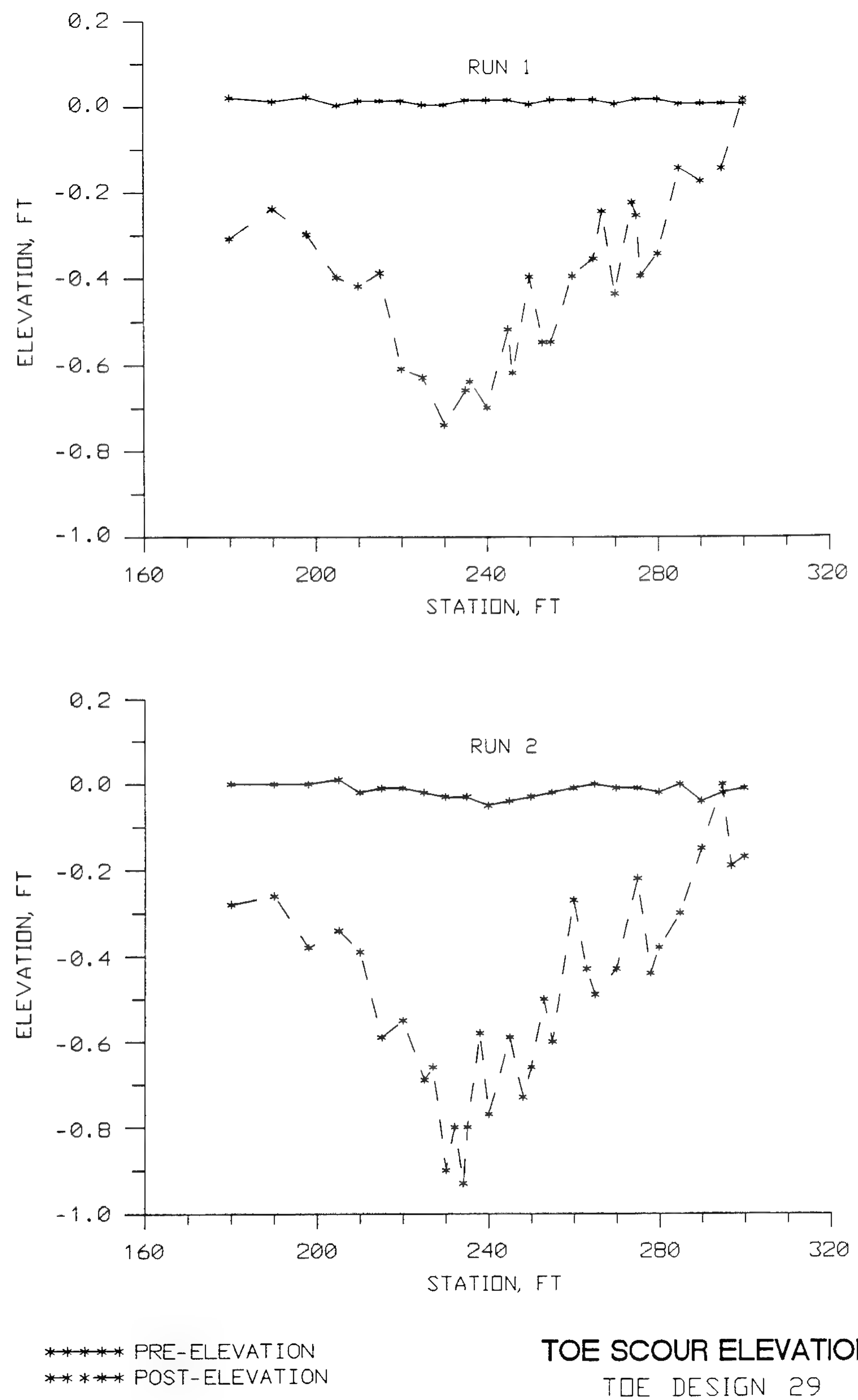
RUN 2



TOE SCOUR ELEVATION

TOE DESIGN 28

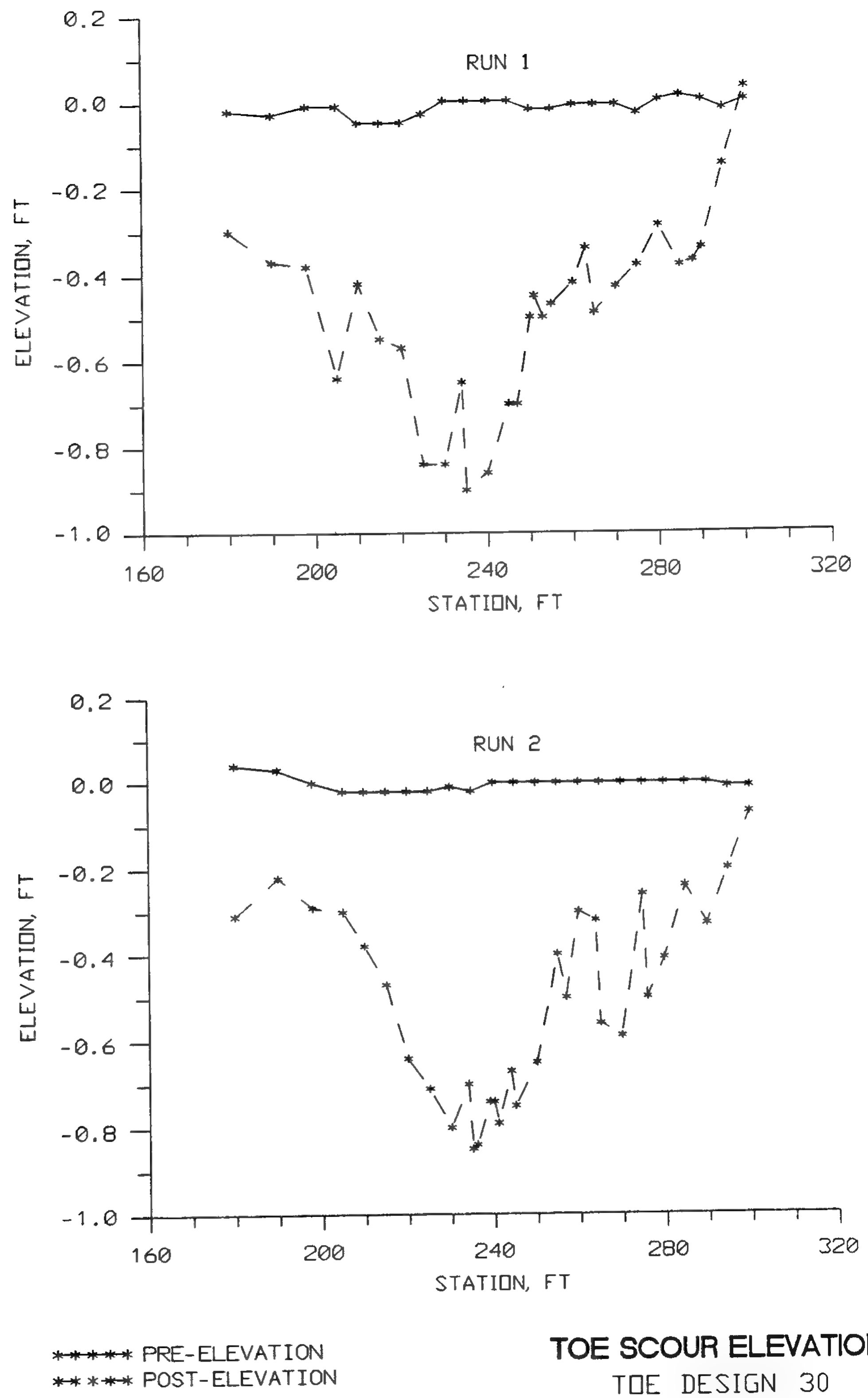
RUNS 1 AND 2



TOE SCOUR ELEVATION

TOE DESIGN 29

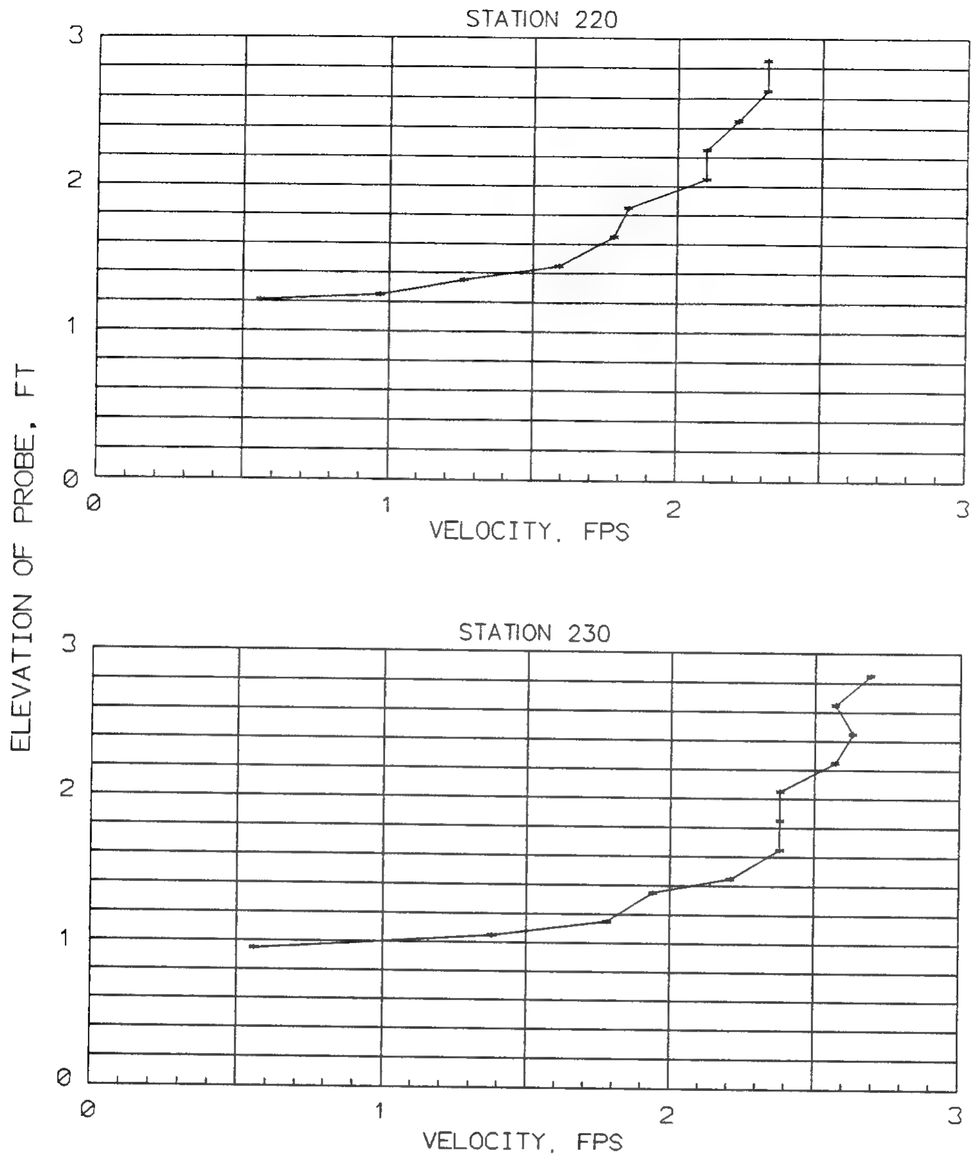
RUNS 1 AND 2



TOE SCOUR ELEVATION

TOE DESIGN 30

RUNS 1 AND 2

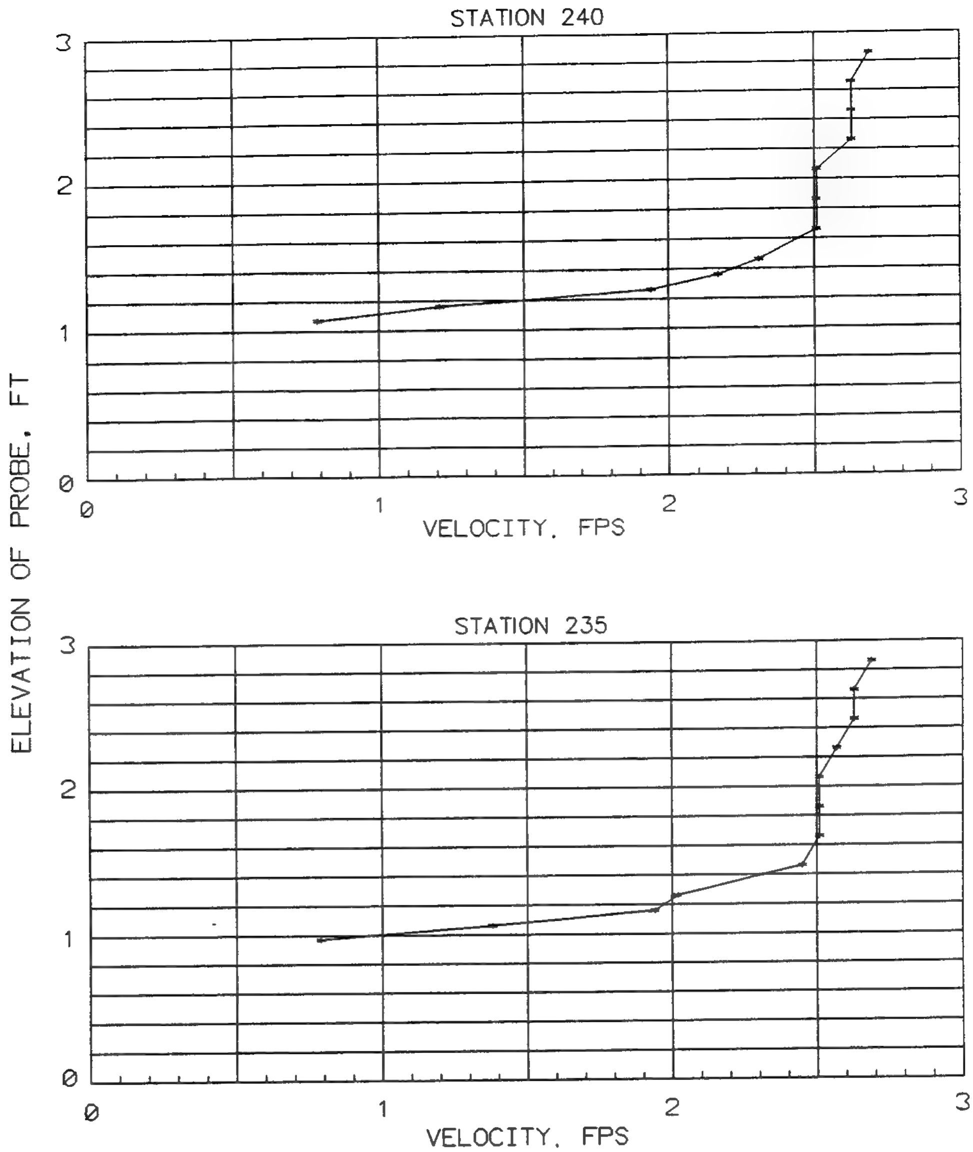


NOTE: PROBE ELEVATIONS

1. WATER-SURFACE STATION 220 = 2.950
2. BOTTOM STATION 220 = 1.205
3. WATER-SURFACE STATION 230 = 2.950
4. BOTTOM STATION 230 = 0.945

NEAR-BANK VELOCITIES

TOE DESIGN 24, RUN 2
STATIONS 220 AND 230

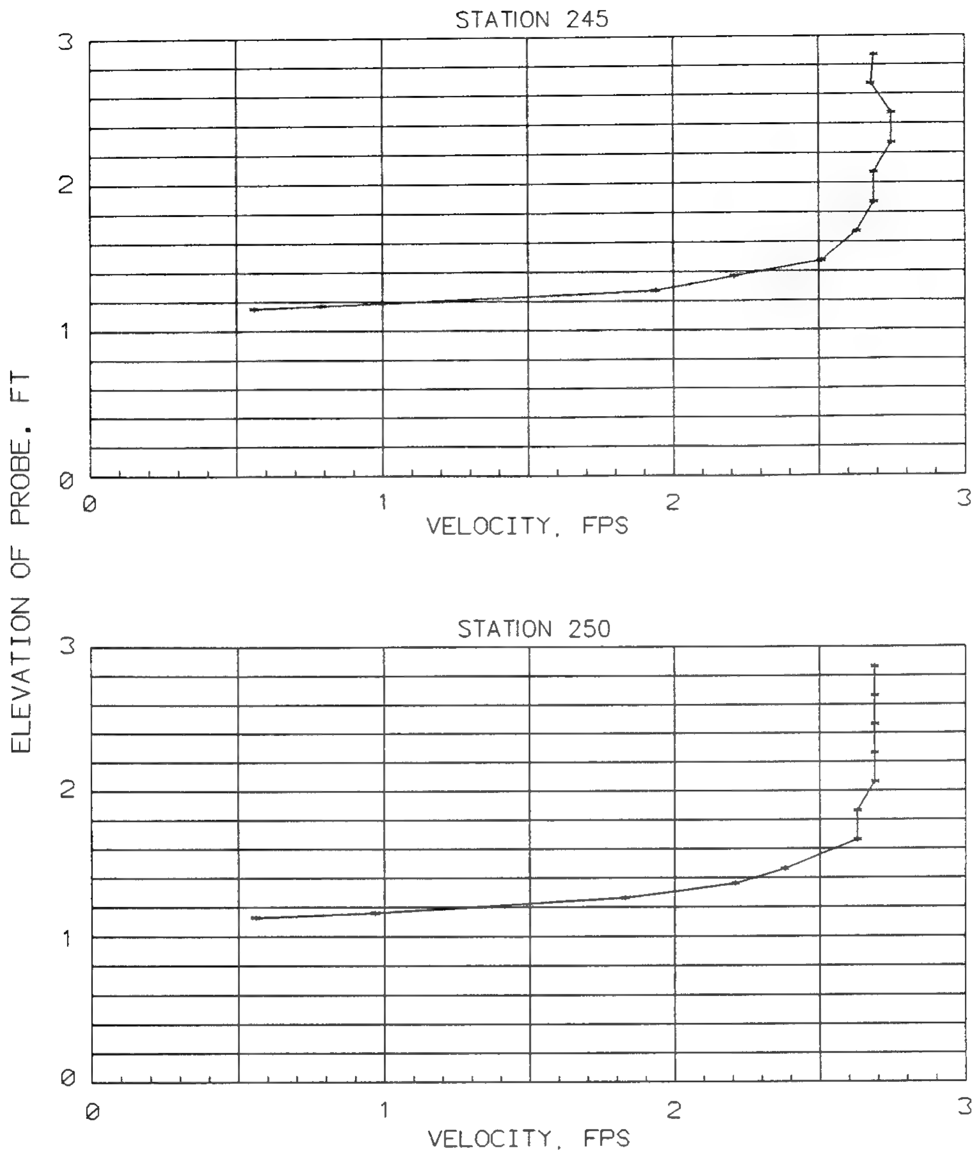


NOTE: PROBE ELEVATIONS

1. WATER–SURFACE STATION 235 = 2.960
2. BOTTOM STATION 235 = 0.960
3. WATER–SURFACE STATION 240 = 2.960
4. BOTTOM STATION 240 = 1.060

NEAR-BANK VELOCITIES

TOE DESIGN 24, RUN 2
STATIONS 235 AND 240

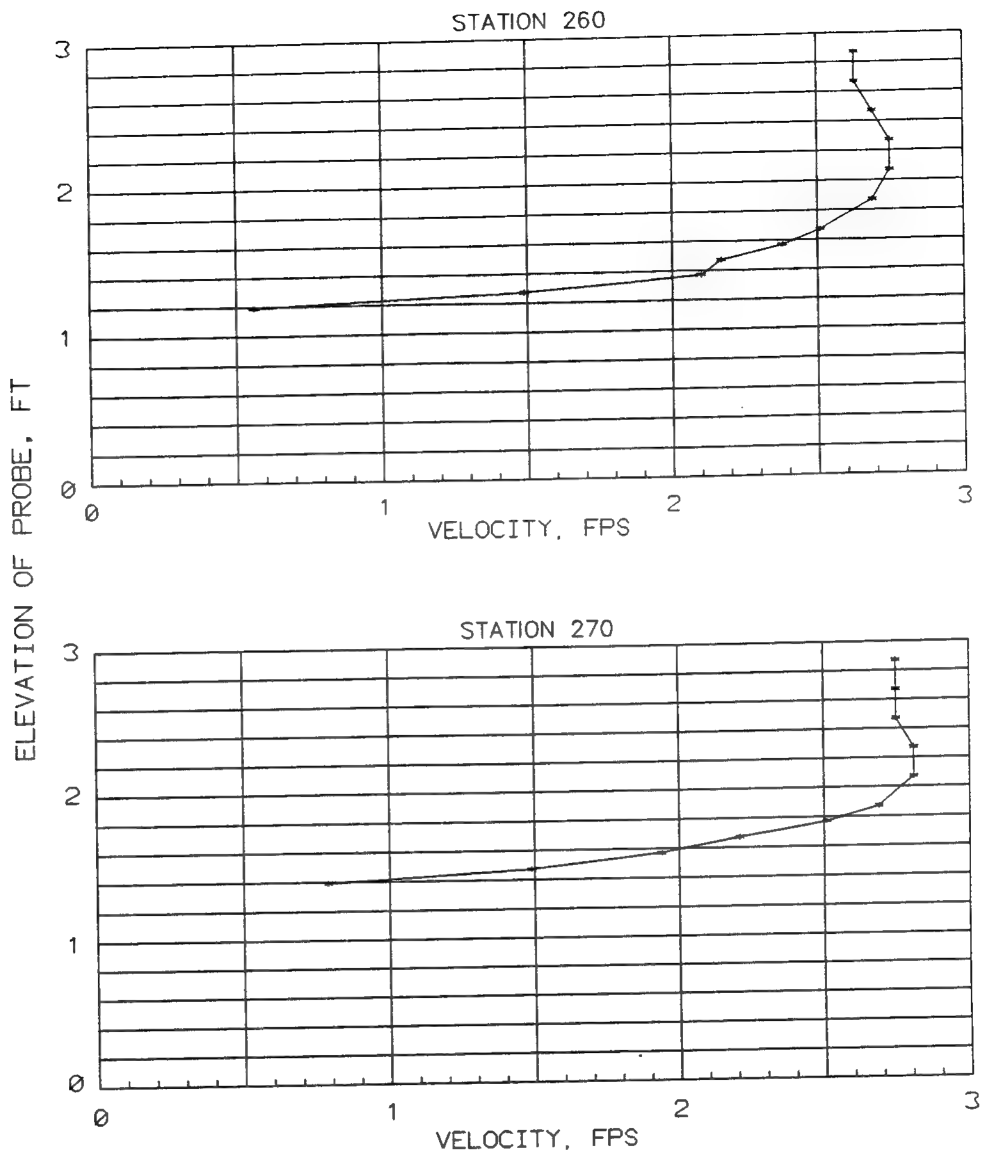


NOTE: PROBE ELEVATIONS

1. WATER–SURFACE STATION 245 = 2.970
2. BOTTOM STATION 245 = 1.145
3. WATER–SURFACE STATION 250 = 2.960
4. BOTTOM STATION 250 = 1.135

NEAR-BANK VELOCITIES

TOE DESIGN 24, RUN 2
STATIONS 245 AND 250

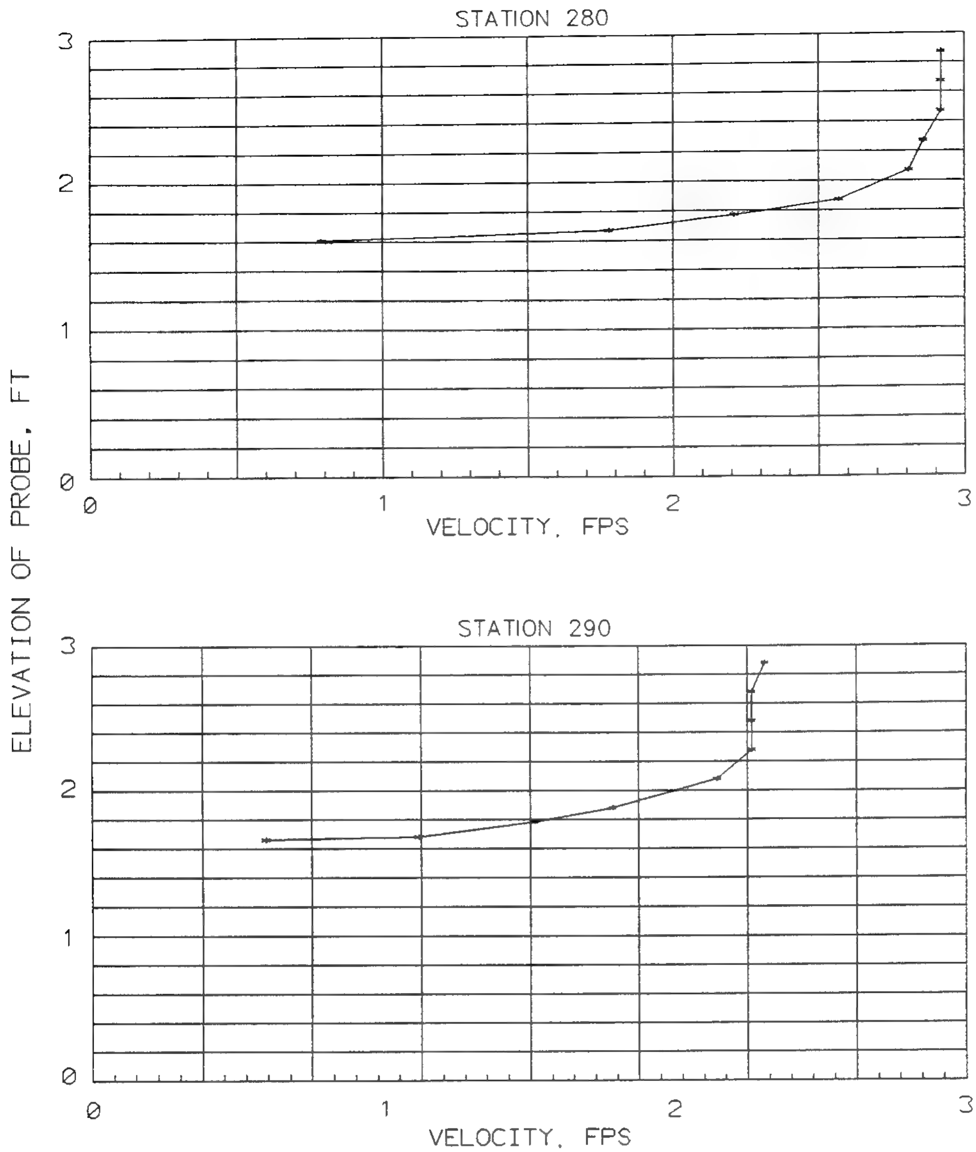


NOTE: PROBE ELEVATIONS

1. WATER-SURFACE STATION 260 = 2.970
2. BOTTOM STATION 260 = 1.185
3. WATER-SURFACE STATION 270 = 2.970
4. BOTTOM STATION 270 = 1.380

NEAR-BANK VELOCITIES

TOE DESIGN 24, RUN 2
STATIONS 260 AND 270



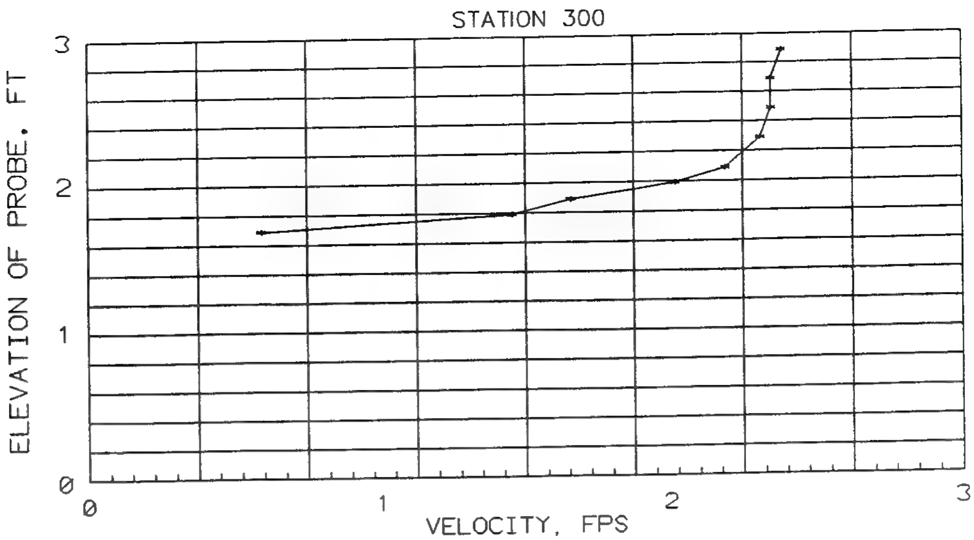
NOTE: PROBE ELEVATIONS

1. WATER-SURFACE STATION 280 = 2.970
2. BOTTOM STATION 280 = 1.600
3. WATER-SURFACE STATION 290 = 2.980
4. BOTTOM STATION 290 = 1.660

NEAR-BANK VELOCITIES

TOE DESIGN 24, RUN 2

STATIONS 280 AND 290

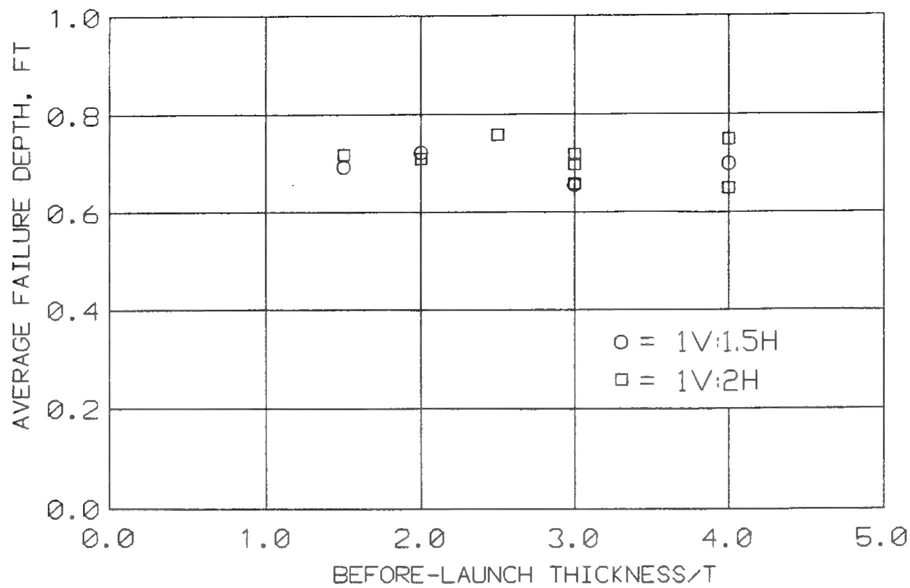


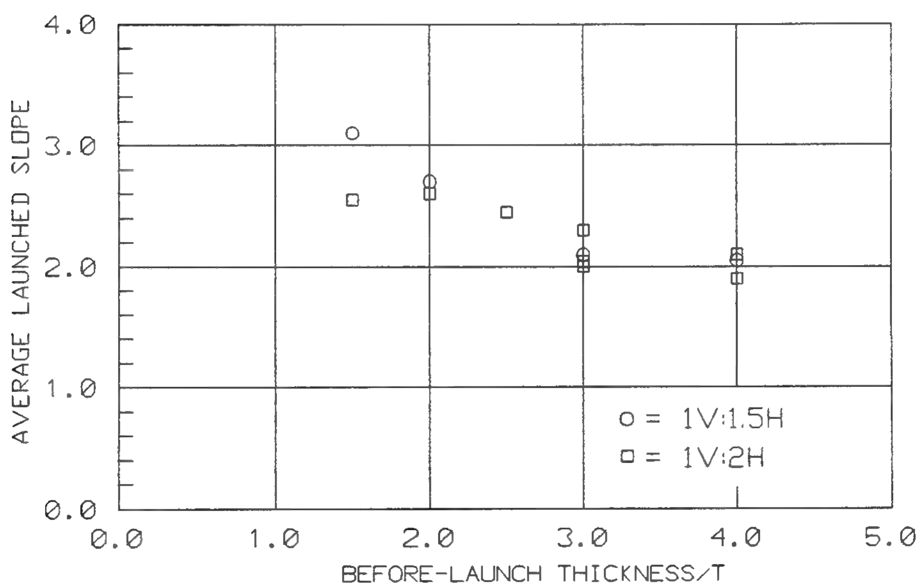
NOTE: PROBE ELEVATIONS

1. WATER-SURFACE STATION 300 = 2.990
2. BOTTOM STATION 300 = 1.690

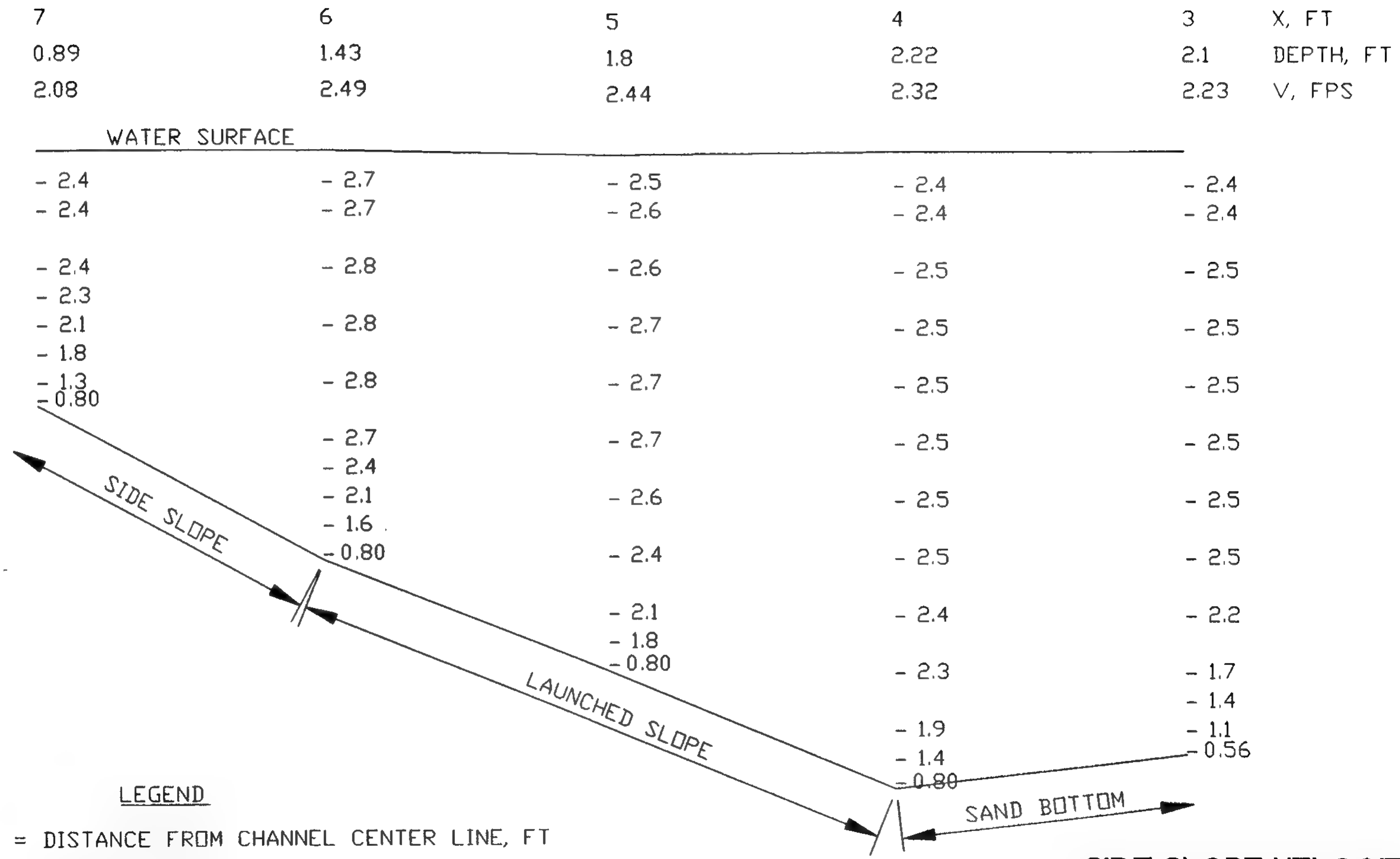
NEAR-BANK VELOCITIES

TOE DESIGN 24, RUN 2
STATION 300





**FAILURE DEPTH AND LAUNCHED SLOPE
VERSUS
BEFORE-LAUNCH THICKNESS/T**



LEGEND

X = DISTANCE FROM CHANNEL CENTER LINE, FT

V = DEPTH-AVERAGED VELOCITY, FPS

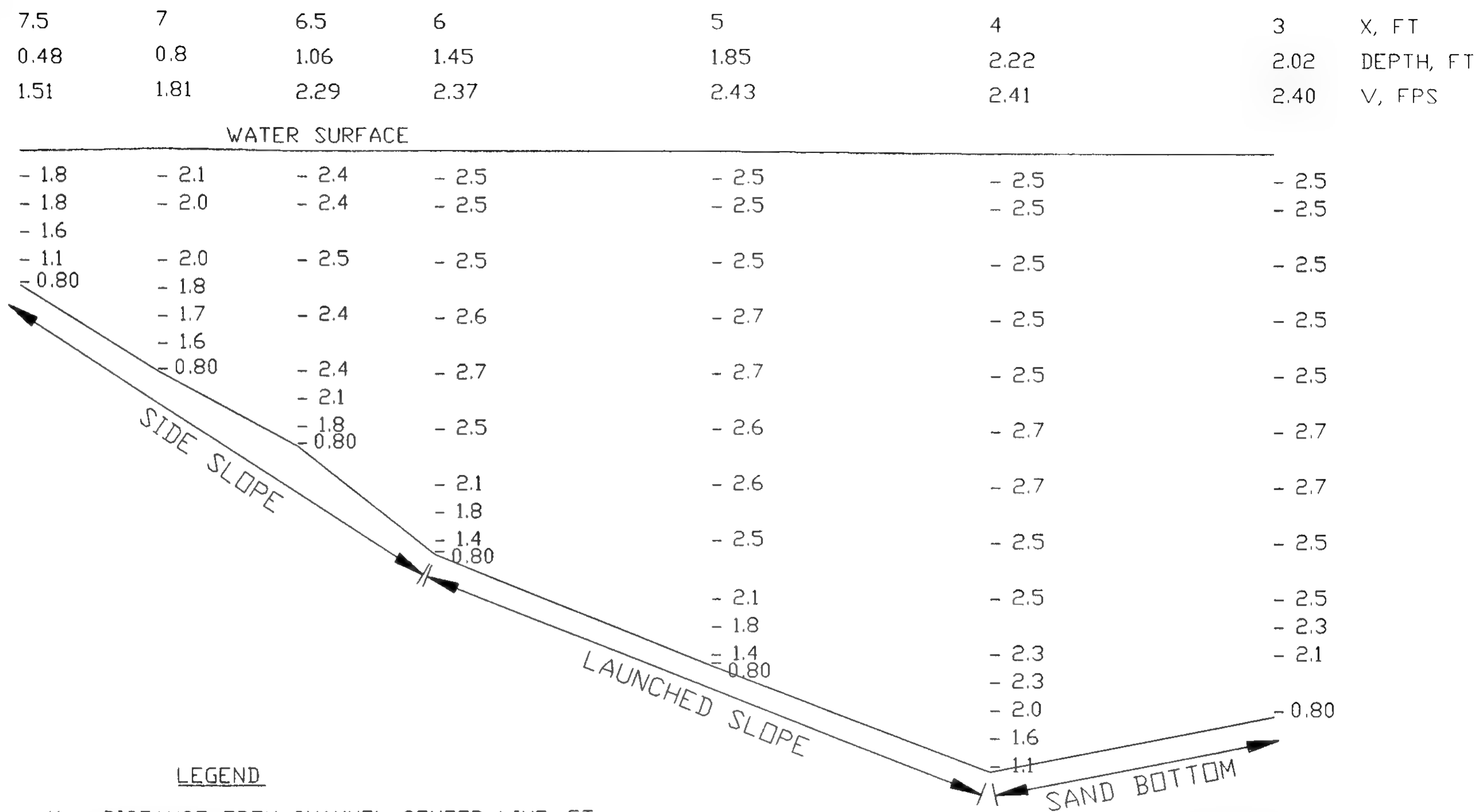
- 3.3 POINT VELOCITY OVER SIDE SLOPE, FPS

NOTE: WATER-SURFACE ELEVATION AT CHANNEL CENTER LINE = 180.485

SIDE SLOPE VELOCITIES

TEST 2S, RUN 1

STATION 255



LEGEND

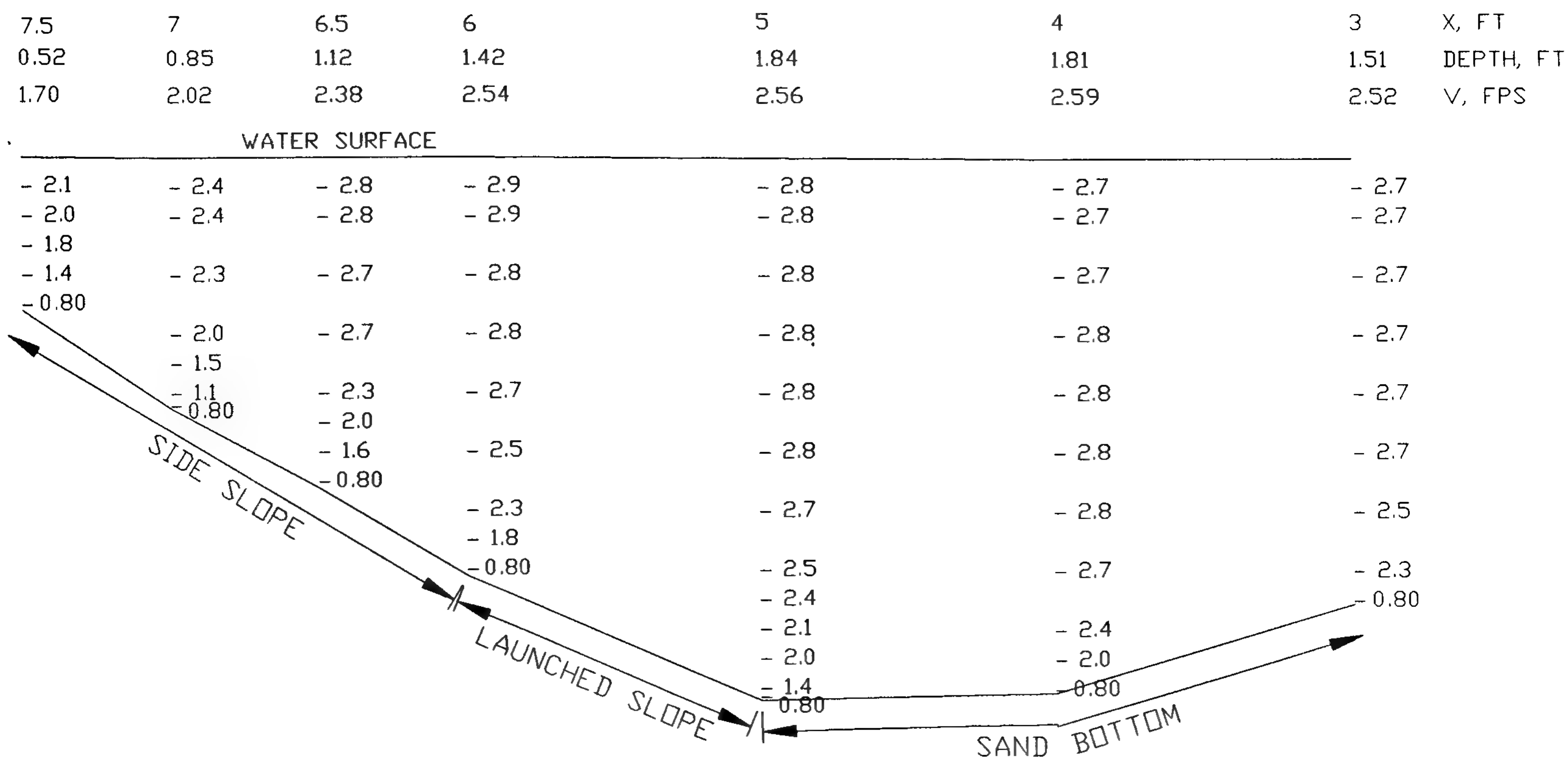
X = DISTANCE FROM CHANNEL CENTER LINE, FT
V = DEPTH-AVERAGED VELOCITY, FPS
- 3.3 POINT VELOCITY OVER SIDE SLOPE, FPS

NOTE: WATER-SURFACE ELEVATION AT CHANNEL CENTER LINE = 180.483

SIDE SLOPE VELOCITIES

TEST 4S, RUN 1

STATION 255



LEGEND

X = DISTANCE FROM CHANNEL CENTER LINE, FT

V = DEPTH-AVERAGED VELOCITY, FPS

- 3.3 POINT VELOCITY OVER SIDE SLOPE, FPS

NOTE: WATER-SURFACE ELEVATION AT CHANNEL CENTER LINE = 180.463

SIDE SLOPE VELOCITIES

TEST 4S, RUN 1

STATION 280

Appendix A
Detailed Test Results

Table A1
Weighted Toe, 1V:1.5H Side Slope Test Results

Test No.	Run No.	Results
3	1	Failure zone; station 2+22 to station 2+58. Filter fabric can be seen at stations 2+35, 2+40 to 2+46, and 2+56 to 2+57.
3	2	Failure zone; station 2+27 to station 2+58. Filter fabric can be seen at stations 2+29, 2+31, 2+35, 2+51, and 2+54.
4	1	Failure zone; station 2+25 to station 2+60.
4	2	Failure zone; station 2+25 to station 2+70. Filter fabric can be seen at stations 2+25 to 2+26, 2+45, 2+58, and 2+68.
5	1	Failure zone; station 2+22 to station 2+47. Filter fabric can be seen at stations 2+28, 2+33, and 2+40.
5	2	Failure zone; station 2+24 to station 2+55. Filter fabric can be seen at stations 2+26, and 2+48 to 2+50. Lost riprap was recovered and measured at three locations: stations 2+31 to 2+34, 2+40 to 2+43, and 2+50 to 2+53. Note: Lost riprap is the riprap that is at bottom of a launched slope that is mostly parallel with the channel bottom and covered by sand.
6	1	Failure zone; station 2+53 to station 2+55. Lost riprap was recovered and measured at stations 2+31 to 2+34, 2+40 to 2+43, and 2+50 to 2+53.
6	2	Failure zone; station 2+47 to station 2+58. Lost riprap was recovered and measured at stations 2+31 to 2+34, 2+38 to 2+41, and 2+52 to 2+55.
7	1	Failure zone; station 2+30 to station 2+56. Gradation No. 14 was used on this test. Small waves or high places were created in launched side slope at stations 2+38, 2+45, and 2+50.
8	1	Failure zone; station 2+30 to station 2+70. Dune locations (trough) at stations 2+64, 2+75, and 2+90. Waves or high places were created in launched slope at stations 2+43 to 2+43, 2+46 to 2+47, 2+51, 2+60, and 2+63.

Table A2
Weighted Toe, 1V:2H Side Slope Test Results

Test No.	Run No.	Results
20	1	Failure zone; station 2+36 to station 2+54. Filter fabric can be seen at station 2+47 to station 2+52. At station 2+70 to station 2+72 filter fabric can be seen but not all toe design riprap is depleted. Dune locations (trough): stations 2+83 and 2+97.
20	2	Failure zone; station 2+34 to station 2+52. Filter fabric can be seen at stations 2+39 to 2+41, 2+47, and 2+51. Dune locations (trough) at stations 2+75, 2+85, and 3+03.
21	1	Failure zone; station 2+27 to station 2+53. Filter fabric can be seen all along failure zone. Dune locations (trough) at stations 2+65, 2+71, and 2+95.
21	2	Failure zone; station 2+30 to station 2+50. Filter fabric can be seen at stations 2+36 to 2+38 and 2+40 to 2+50. Dune locations (trough) at stations 2+65, 2+71, and 2+95.Note: Not as much failure zone as Test 21, run 1.
		Note: Not as much failure zone as Test 21, run 1.
21	3	Failure zone; station 2+28 to station 2+37. Dune locations (trough) at stations 2+40, 2+50, 2+64, 2+75, and 2+84. Note: Overall this toe design appears to be a very good toe design. Short failure zone.
22	1	Failure zone; station 2+33 to station 2+56. Filter fabric can be seen at stations 2+33, 2+41 to 2+49, and 2+52 to 2+55. Dune locations (trough) at stations 2+64, 2+75, 2+85, and 2+98.
22	2	Failure zone; station 2+25 to station 2+50. Filter fabric can be seen at stations 2+25 and 2+38 to 2+42. Dune locations (trough) at stations 2+66, 2+77, 2+84, and 2+94. Note: Station 2+11 to station 2+13 filter fabric can be seen at toe of slope. This cannot be considered a failure point because a moderate amount of toe design riprap still remains.
23	1	Failure zone; station 2+25 to station 2+65. Filter fabric can be seen all along failure zone from station 2+34 to 2+54 (not solid) and station 2+61 to 2+65. Dune locations (trough) at stations 2+43, 2+49, 2+57, 2+70, 2+80, and 2+95. Note: At stations 2+23, 2+69, 2+73, and 2+77, all toe design riprap is not depleted but filter fabric is exposed at lower edge of slope.
23	2	Failure zone; station 2+27 to station 2+70. Filter fabric can be seen at stations 2+28, 2+35, 2+54, and 2+68. Dune locations (trough) at stations 2+44, 2+48, 2+64, 2+73, and 2+85.
24	1	Failure zone; station 2+29 to station 2+58. Filter fabric can be seen at stations 2+33, 2+37, 2+41, 2+46, and 2+50. Dune locations (trough) at stations 2+36, 2+47, 2+58, 2+67, 2+78, and 2+90. Note: This test was run for 13 hr.
24	2	Failure zone; station 2+35 to station 2+50. Filter fabric can be seen at stations 2+40 to 2+41, 2+44 to 2+46, and 2+47 to 2+49. Dune locations (trough) at stations 2+38, 2+47, 2+67, 2+75, and 2+95. Note: After completion of 13-hr test, model was restarted and velocity measurements were taken at stations 2+20, 2+30, 2+35, 2+40, 2+50, 2+60, 2+70, 2+80, 2+90, and 3+00.
25	1	Failure zone; station 2+36 to station 2+54. Filter fabric can be seen at station 2+43 to 2+44. Dune locations (trough) at stations 2+45, 2+53, 2+58, 2+71, and 2+85.

(Continued)

Table A2 (Concluded)		
Test No.	Run No.	Results
26	1	Failure zone; station 2+36 to station 2+55. At stations 2+60 to 2+65 and 2+66 to 2+68 most all toe design riprap is depleted, but no launching of green side slope riprap. No holes where filter fabric can be seen. More of gradation 15 seems to be staying on green colored side slope riprap in failure zone than gradation 6 did in previous test. Dune locations (trough) at stations 2+48, 2+58, 2+68, 2+78, and 2+95.
26	2	Failure zone; station 2+32 to station 2+55. at Station 2+62 to station 2+68 most all toe design riprap is depleted, but no launching of side slope riprap. Hole in side slope at station 2+68 could be caused by velocity of water because gradation 15 was undersized for 40-cfs flow. High and low places showing up in launched slope in failure zone. Station 2+68 was a low place. Dune locations (trough) at stations 2+50, 2+60, 2+65, and 2+86.
27	1	Failure zone; station 2+30 to station 2+55. Very little launching of green side slope rirrap in failure zone. At station 2+73 to station 2+74 most all toe design riprap is depleted, but no launching of green side slope riprap. No high and low places showing up in failure zone. Dune locations (trough) at stations 2+57, 2+69, 2+74, and 2+57.
27	2	After 4.5 hr most all toe design riprap was depleted, and green colored side slope riprap was starting to show at stations 2+38 to 2+40 and 2+44 to 2+57. Failure zone at station 2+38 to station 2+37. No launching of green side slope riprap in failure zone. Dune locations (trough) at stations 2+29, 2+35, 2+43, 2+52, 2+58, 2+66, and 2+72.
		After 9.0 hr: All toe design riprap was depleted and green colored side slope riprap was showing at stations 2+27, 2+30, 2+33, 2+35 to 2+37, 2+38 to 2+42, and 2+44 to 2+57. Some launching of green side slope riprap in failure zone. Dune locations (trough) at stations 2+40, 2+49, 2+54, 2+63, 2+73, 2+82, and 2+94.
		After 13.0 hr: Stations where toe design riprap was depleted and green colored side slope riprap was showing was the same as after 9.0 hr. Failure zone at stations 2+25 to 2+57. Failure zone was no larger than after 9.0 hr, but more launching of green colored side slope riprap. Dune locations (trough) at stations 2+37, 2+45, 2+51, 2+57, 2+72, 2+77, and 2+83.

Table A3
Midbank Design, 1V:2H Side Slope Test Results

Test No.	Run No.	Results
28	2	Failure zone; station 2+25 to station 2+70, station 2+85 to station 2+90. Failure at station 2+85 to station 2+90 might be caused by discharge being too high or gradation 6 riprap being undersized for this midbank design. Filter fabric exposed at stations 2+30 to 2+34, 2+38 to 2+44, 2+45 to 2+48, 2+49 to 2+53, 2+57 to 2+64, and 2+86 to 2+88. High and low places in launched slope at stations 2+30 to 2+34, 2+40 to 2+44, 2+45 to 2+47, 2+49 to 2+53, 2+58 to 2+65, and 2+85 to 2+90. Dune locations (trough) at stations 2+44, 2+50, 2+68, and 2+82.
28	2	Failure zone; station 2+25 to station 2+77. At stations 2+80 to 2+83 and 2+86 to 2+87 all midbank design riprap was depleted, but no launching of black painted side slope riprap. Filter fabric was exposed at stations 2+29 to 2+37, 2+42 to 2+45. 2+54, 2+63, and 2+75. High places in launched slope at stations 2+36, 2+40, 2+47, 2+55, 2+64, and 2+74. Dune locations (trough) at stations 2+35, 2+44, 2+50, 2+65, and 2+78.
29	1	Test was run for 8 hr. Failure zone at station 2+30 to station 2+50. Station 2+50 to station 2+68 still had a light amount of midbank design riprap that was not depleted. Filter fabric was exposed at stations 2+45 and 2+48. Dune locations (trough) at stations 2+36, 2+46, 2+53, 2+64, 2+70, and 2+76.
29	2	Failure zone; station 2+24 to station 2+59. At stations 2+63 to 2+65 and 2+72 to 2+78 all midbank design riprap was depleted, but no launching of side slope riprap. Filter fabric was exposed at stations 2+32 to 2+33, 2+35, 2+36, 2+40, 2+42, 2+44 to 2+46, and 2+48. Dune locations (trough) at stations 2+34, 2+40, 2+48, 2+55, 2+63, 2+78, and 2+91.
30	1	Failure zone; stations 2+24 to 2+64 and 2+85 to 2+89. At station 2+64 to station 2+85 most all midbank design riprap was depleted, but no launching of red painted side slope riprap. Filter fabric was exposed at stations 2+24, 2+26 to 2+28, 2+29 to 2+30, 2+36, 2+39 to 2+47, 2+49 to 2+50, 2+63, and 2+87. Dune locations (trough) at stations 2+46, 2+52, 2+64, 2+75, 2+88, and 2+95.
30	2	Failure zone; station 2+30 to station 2+69. At stations 2+71 to 2+80, 2+85 to 2+86, and 2+94 to 2+96 most all midbank design riprap was depleted, but no launching of black painted side slope riprap. Filter fabric was exposed at stations 2+31 to 2+32, 2+34 to 2+36, 2+41, to 2+42, 2+49 to 2+50, 2+62, and 2+64 to 2+68. Dune locations (trough) at stations 2+35, 2+39, 2+42, 2+45, 2+50, 2+57, 2+64, 2+76, and 2+86. High places in launched slope at stations 2+26, 2+34, 2+37, 2+45, 2+51, 2+70, 2+80, and 2+97.

Table A4
Launched Stone Stability Test Results

Test No.	Run No.	Results
1S	1	Failure; major failure station 2+45 to 2+56. Four locations covering entire width of filter fabric at stations 2+45, 2+52, 2+54 to 2+55, and 2+56. Minor failure station 2+56 to 2+65. Note: Gradation 12 riprap was undersized.
2S	1	Failure; major failure station 2+45 to 2+52, minor failure station 2+52 to 2+65. Two holes in riprap ranged from 2 to 12 in. in diameter. Four holes were at top half of filter fabric. All other holes were at bottom half of filter fabric. Note: Gradation 14 riprap was undersized.
3S	1	Failure: Major failure each at stations 2+45 and 2+65 covering entire width of test section. Some smaller holes station 2+47 to 2+54 on lower half of test section where filter fabric can be seen. At stations 2+59 to 2+60 lower 2 in. of filter fabric can be seen.
4S	1	Failure; at station 2+73 to 2+85 filter fabric can be seen along lower edge of test section. Highest area of movement station 2+77 to 2+82. Hole 8 in. long by 4 in. wide at station 2+79. No movement along upper 1 ft of test section.
5S	1	Borderline; very little movement over entire length of test section. One small hole 2 in. in diameter at station 2+42 on lower 6 in. of filter fabric. At stations 2+40 to 2+49, 2+52 to 2+56, and 2+73 to 2+75 scour zone is below lower edge of filter fabric. Riprap that was placed at bottom of filter fabric for added protection launched down into scour zone and protected test section from failure.

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13. ABSTRACT *(Maximum 200 words)*

An empirical method for scour depth estimation is developed based on radius/width and aspect ratio. The thickness of the before-launch section controls the rate at which rock is released and should be 2.5 to 4.0 times the thickness of the bank protection revetment T for gradual scour and 2.5 to 3.0 T for rapid scour found in impinged flow environments. Riprap size for gradual scour is the same for both launched riprap and riprap placed by standard construction methods. Stone volume requirements are presented as a function of scour depth and whether the launch section is placed in the dry or underwater. Gradations having $D_{85}/D_{15} \geq 2$ are recommended for launched riprap sections to prevent leaching of bank material through the launched riprap.

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